**GEORGIA INSTITUTE OF TECHNOLOGY**
**OFFICE OF CONTRACT ADMINISTRATION**
**SPONSORED PROJECT INITIATION**

Date: May 31, 1978

Project Title: Continued Development and Application of Some Fast Neutron Dosimetry Techniques Utilizing Plastic Track Detectors for Radiotherapy and Health Physics

Project No: E-26-632

Project Director: Dr. Karl Z. Morgan

Sponsor: Department of Energy; Oak Ridge Operations

Agreement Period: From 12/1/77 Until 11/30/78

Type Agreement: Contract No. EY-76-S-05-4814 (Mod. No. A005)

Amount: $33,500

Reports Required: Publication Preprints; Publication Reprints; Progress Report; Final Report

Sponsor Contact Person (s):

Technical Matters

Robert L. Butenhoff
Physical and Technological Programs
Division of Biomedical and Environmental Research
U.S. Department of Energy
Washington, D.C. 20545

Contractual Matters

(thru OCA)
Mr. Walker Love
Research Contracts, Procedures and Reports Branch
Contract Division
U.S. Department of Energy
Oak Ridge Operations
P.O. Box E
Oak Ridge, TN 37830
615/483-8611, ext. 34105

Defense Priority Rating: none

Assigned to: Nuclear Engineering (School/Laboratory)

COPIES TO:

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- Division Chief (EES)
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- Other

CA-3 (3/76)

Porter

**GEORGIA INSTITUTE OF TECHNOLOGY**
**OFFICE OF CONTRACT ADMINISTRATION**

## SPONSORED PROJECT TERMINATION

Date: March 13, 1979

Project Title: Continued Development and Application of Some Fast Neutron Dosimetry Techniques Utilizing Plastic Track Detectors for Radiotherapy and Health Physics

Project No: E-26-632

Project Director: Dr. Karl Z. Morgan

Sponsor: Department of Energy, Oak Ridge Operations

Effective Termination Date: November 30, 1978

Clearance of Accounting Charges: November 30, 1978

Grant/Contract Closeout Actions Remaining:

NONE

TERMINATED

_ Final Invoice and Closing Documents
_ Final Fiscal Report
_ Final Report of Inventions
_ Govt. Property Inventory & Related Certificate
_ Classified Material Certificate
_ Other _____

NOTE: Continued by E-26-642

Assigned to: Nuclear Engineering (School/Laboratory)

COPIES TO:

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CA–4 (1/79)

E-26-632

# PROPOSAL FOR RENEWAL OF CONTRACT EY-76-S-05-4814 AND TO CONTINUE DEVELOPMENT AND APPLICATION OF SOME FAST NEUTRON DOSIMETRY TECHNIQUES UTILIZING PLASTIC TRACK DETECTORS FOR RADIOTHERAPY AND HEALTH PHYSICS

Submitted to the

Department of Energy

by the

School of Nuclear Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Karl Z. Morgan
Co-Principal Investigator

Shian-Jang Su
Co-Principal Investigator

and two new graduate students, Michael Edward Sanders and Dorothy Rea

Lynn E. Weaver
Director, School of Nuclear Engineering

Dwight L. Allen, Deputy Director
Office of Contract Administration

PROPOSAL FOR RENEWAL OF CONTRACT EY-76-S-05-4814 AND TO CONTINUE DEVELOPMENT AND APPLICATION OF SOME FAST NEUTRON DOSIMETY TECHNIQUES UTILIZING PLASTIC TRACK DETECTORS FOR RADIOTHERAPY AND HEALTH PHYSICS

by

Karl Z. Morgan and Shian-Jang Su

## Abstract

Research in the area of electrochemical etching has been attracting increasing interest for many health physics uses and radiotherapeutic applications. A few of the studies of interest which we propose to continue and carry out in the coming year include completion of $^{239}Pu$ bone dosimetry, extensions of our bone dosimetry technique, epithermal neutron dosimetry and a more detailed examination of the two distinct track sizes from alpha irradiations which were discovered during the present investigations and and are being announced in scientific journals at the present time. This discovery of two distinct alpha track sizes is particularly exciting because it provides the possibility of developing a system of dosimetry that corrects for LET. Investigation of these problems is expected to make a major contribution to the fields of alpha particle and neutron dosimetry.

TABLE OF CONTENTS

## Introduction

The complete results to date of our research in the field of electrochemical etching of polycarbonate foils for the purpose of dosimetry have been accumulated and appear in (ORO-4914-5) and our progress reports dated August 1977 and August 1978. These reports show the intensive research done by the investigators in the field as well as some recommendations for the solution of new problems for the advancement of this rapidly developing and interesting type of dosimetry to many dosimetry applications. Some of the recommended studies are already under investigation and preliminary results have been presented at several scientific meetings including the American Physical Society, Auburn, Alabama, 1975; Health Physics Society, Denver, Colorado, 1976 and San Francisco, 1976; International Radiation Protection Association, Amsterdam, The Netherlands, 1975; the American Industrial Hygiene Association, Atlanta, Georgia, 1976; the Health Physics Society, Atlanta, Georgia, 1977; the American Nuclear Society, Raleigh, North Carolina, 1977 and Gainesville, Florida, 1978; and the Health Physics Society, Minneapolis, Minnesota, 1978. (Copies of these reports have been sent to the Washington office of DOE, but an additional complete set of reprints is appended to this project renewal proposal.

Many of the problems we have listed under this contract are being investigated actively at present, including completion of the $^{239}Pu$ bone dosimetry study and the thermal and epithermal neutron studies. These projects will be completed in the new contract year and the other interesting problems mentioned here will be examined more intensively and in greater detail.

## Proposed New Research

The following proposals for continued research into the field of electrochemical etching of polycarbonate foils are but a few of the promising avenues of research and application of this technique. This new development offers the promise of information hitherto unachievable in the field of health physics by prevailing dosimetry methods such as the use of thick photographic emulsions with proton track counting (a technique which one of us [KZM] first introduced to health physics in 1944). Descriptions of the major problems of current interest to us are as follows:

### Completion of $^{239}$Pu Bone Dosimetry in Human and Dog Bones

We have now completed calibration procedures for the electrochemical etching system using polycarbonate foils for alpha particles. Through the generosity of Dr. W. S. S. Jee at the University of Utah one of us (Stillwagon) was priviledged to work 10 days at the Radiobiology Laboratory at the University of Utah and returned with approximately 150 bone samples from beagle dogs prepared for our applications. Present status of this work involves taking of data from the exposed foils and this portion of the study including submission of results for publication should be completed within a few months.

### Thermal and Epithermal Neutron Dosimetry

Our electrochemical etching system has previously been used as a fast neutron dosimetry system. Now we are extending this system to thermal neutron dosimetry by placing thin tablets of $^{6}$Li over a portion of the foils to interact with thermal neutrons in the (n,$\alpha$) reaction ($\sigma_c \simeq 953$b). A tablet of $^{7}$Li is placed on top of the $^{6}$Li to obtain even compression

against the foil. The alpha particles emitted then create tracks in the polycarbonate foils, the number being proportional to the initial fluence of thermal neutrons. This study also is nearing completion.

Extension of this contract involves also modifications of present techniques in order that this method of dosimetry include measurement of dose from epithermal neutrons as well as from fast and thermal neutrons. The epithermal region is an extremely difficult one in which to evaluate absorbed dose to tissue and such dosimetry has been largely neglected. We feel this study is important and could make a significant contribution to the field of neutron personnel dosimetry by providing a system that will measure neutron dose over an energy range of 0.025 eV to 50 MeV.

Extensions of Our Bone Dosimetry Techniques

We would like to investigate other uses for the general technique we have developed for bone dosimetry. We propose to vary exposure time of the foils to our bone samples, use samples of different plutonium content and use small cubes of trabecular bone tissue rather than large infinitely thick planes to obtain the microdose distribution in three dimensions. Additionally we can examine the adaptability of the general technique to the dosimetry of other tissues, e.g., lung, pulmonary lymph nodes, liver and gonads--to which the dose from plutonium is of current interest and controversy.

Two Sizes of Alpha Particle Tracks

As reported in our August 1977 and 1978 Progress Reports, we have observed two categories of tracks on our foils after exposure to alpha emitters and employment of our electrochemical etching techniques. It has been proposed the larger tracks are due to carbon and oxygen recoils.

This could be verified by irradiation of foils by accellerator produced alpha particles of various energies then by carbon nuclei produced in an accellerator. The frequency histograms of the track diameters could then be compared. If the energies of the accelerator produced helium and carbon nuclei were chosen carefully, the ratio of small to large tracks should vary in accordance with the theory we have developed. Other possibilities are the use of polarized alpha particles, selected to maximize the interaction cross-section with carbon and oxygen muclei to attempt to increase the numbers of large tracks, thereby proving their origin.

## Proposed Budget

Contract No. EY-76-S-05-4814

Cost Estimate for Period
December 1, 1978 to November 30, 1979

| | | | |
|---|---|---|---|
| A. | Direct Salaries and Wages: | | $17,900 |
| | Principal Investigators: | | |
| | Karl Z. Morgan (Principal Investigator) | $9,000 | |
| | Shian J. Su* | 1,050 | |
| | Michael Edward Sanders* | 3,150 | |
| | Dorothy Rea* | 4,200 | |
| | Secretarial Time | 500 | |
| | Retirement Benefits (9.83 of applicable Salaries and Wages | | 934 |
| | Total Direct Salaries, Wages & Retirement Benefits | | 18,834 |
| B. | Equipment | | 1,408 |
| C. | Materials Publication Costs | | 494 |
| D. | Travel | | 1,000 |
| E. | Indirect Costs | | |
| | At a predetermined fixed rate of 76% of Salaries and Wages as established by the Naval Material Command upon advisory audit by the Defense Contract Audit Agency | | 14,314 |
| | TOTAL PROJECT COST | | $35,050** |

| | |
|---|---|
| Total actual project cost for the current period (through 11/30/78) | $33,500 |
| Total actual and estimated cost chareable to DOE for the new period | $36,050 |

*Graduate Students

**$33,500 + $2,550 to cover increase in overhead from $11,764 to $14,314

## Duration of the Proposed Research

The proposed research is intended to be completed within a period of 12 months which will last from December 1, 1978 to November 30, 1979.

## Project Personnel

Karl Ziegler Morgan was born in Enochsville, North Carolina on September 27, 1907. He received the A.B. and M.A. degrees from the University of North Carolina in 1929 and 1930, respectively, and the Ph.D. degree in physics from Duke University in 1934. From 1934 to 1943 he was chairman of the Physics Department of Lenoir Rhyne College, and during this period did research in cooperation with Duke University in the field of cosmic ray showers, the meson lifetime, etc., in Linville Caverns, on Mt. Mitchell, Beech Mountain, Mt. Evans, etc.

He joined the Metallurgical Laboratory staff at the University of Chicago in the spring of 1943. Here he was one of a group of six persons who developed and established the new science and profession of health physics. During the fall of 1943, he transferred to Oak Ridge National Laboratory where, until the latter part of 1972, he was Director of the Health Physics Division which was engaged in research, engineering, and applied problems. Upon leaving Oak Ridge National Laboratory, he joined the faculty of the Georgia Institute of Technology as Neely Professor in the School of Nuclear Engineering.

In 1956, he was the first president of the Health Physics Society, and from 1966 to 1970 was the first president of the International Radiation Protection Association which has about 10,000 members in some 65 countries. He now is President Emeritus of IRPA, an Emeritus member of

the Main Commission of ICRP, and a member of NCRP. For 20 years he was chairman of the committees of ICRP and NCRP dealing with maximum permissible internal dose of radioisotopes. He has published over 300 papers dealing with subjects of cosmic rays, radiation protection, istrumentation, internal dose, and general health physics. He is past editor of the journal HEALTH PHYSICS.

In 1962, K. Z. Morgan and W. Binks (England) were awarded the first gold medals for meritorious work in the field of radiation protection by the Royal Academy of Science of Sweden.

Dr. Morgan received the Distinguished Alumni Award and the honorary Doctor of Science Degree from Lenoir Rhyne College, honorary membership in Sigma Pi Sigma from Berea College, and the First Distinguished Service Award of the Western Chapter of the Health Physics Society. He is a member of the Health Physics Society, the International Radiation Protection Association, the American Public Health Association, the American Association for the Advancement of Science, the American Industrial Hygiene Association, the Research Society of America, the Radiation Research Society, the Society of Nuclear Medicine, the American Association of Physicists in Medicine, the American Association of Physics Teachers, an Associate Fellow of the American College of Radiology, a Fellow of the American Physical Society and of the American Nuclear Society, and an Affiliate of the Royal Society of Medicine.

Major Reports and Publications

Over 300 papers and publications have been written. Those of major importance over the past few years are as follows:

"Common Sources of Human Exposure to Ionizing Radiation in the United States," American Engineer, July 1968

"Ionizing Radiation: Benefits Versus Risks," Annual Meeting of the Health Physics Society, June 16-20, 1968, Denver, Colorado; and published in Health Physics, Vol. 17, No. 4

"Assumptions Made by the Internal Dose Committee of the International Commission on Radiological Protection," Sixth Annual Meeting of the Gesellschaft fur Nuclearmedizin, Wiesbaden, Germany, September 26-28, 1968; Published in Proceedings, 1969

"Redirecting Health Physics Studies to Areas of Greatest Interest," First European Congress of the International Radiation Protection Association, Menton, France, October 9-11, 1968; Published in Proceedings, 1968

"Development of Health Physics as a Profession," Proceedings of First International Congress of Radiation Protection, Rome, Italy, Vol. 1, 3, Pergamon Press, 1968

"The Need for Standardization Procedures in the Application of Ionizing Radiation to Medical and Dental Patients," Seminar sponsored by the National Center for Radiological Health, Rockville, Maryland, November 15, 1968, Seminar Paper 003

"The Proper Working Level of Radon and Its Daughter Products in the Uranium Mines of the United States," Hearing on Radiation Standards for Mines, Washington, D.C., November 20, 1968; Congressional Record, 1968

"Supplemental Statement on the Proper Working Level of Radon and Its Daughter Products in the Uranium Mines of the USA," Supplement to Testimony presented on November 20, 1968, Washington, D. C.; Congressional Record, 1968

"Future Opportunities in Health Physics," Health Physics Society Midyear Topical Symposium, Los Angeles, California, January 29-31, 1969

"Risks from Diagnostic X-Rays," Yale Scientific, Vol. XLII No. 5, February 1969; Reprinted from Yale Scientific in the Journal of the American Radiography Technologists, Vol. XIV, No. 4, Winter 1969

"Radiation Standards for Reactor Siting," Testimony presented before the Joint Committee on Atomic Energy at its Hearings on Environmental Effects of Producing Electrical Power, Phase 2, January 1970; Congressional Record

"Energy Pollution of the Environment," Midyear Symposium of the Health Physics Society, Louisville, Kentucky, January 28, 1970; Proceedings published in USPHS-BRH Series, BRH/DEP-70-26 Oct. 1970

"A Time of Challenge to the Health Physicist," Presidential Address presented before the Second International Congress on Radiation Protection, May 8, 1970, Brighton, England; Health Physics, Vol. 20, May 1971, pp. 491-498

"My Opinion--You Can Drastically Cut X-Ray Exposure Below Today's Levels," Consultant, March/April 1970

"History of the Health Physics Society," published as part of the RSNA Symposium on the Critical History of American Radiology (Nov. 1970)

"Standard Man-Standard Patient," Medical Radioisotopes: Radiation Dose and Effects, AEC Series 20, p. 87, June 1970

"History of the International Radiation Protection Association," published in Proceedings of the RSNA Symposium on the Critical History of American Radiology, November 1970

"Criteria for the Control of Radioactive Effluents," IAEA Symposium on Environmental Aspects of Nuclear Power Stations, UN Building, New York, August 1970, Proceedings published, this paper is IAEA-SM-146/10; synopsis published also in Environmental Studies, 1971

"Maximum Permissible Levels of Exposure to Ionizing Radiation," International Summer School on Radiation Protection, Boris Kidric Institute of Nuclear Sciences, Cavtat, Yugoslavia, September 20-30, 1970; Proceedings published in 1971 under title of "Radiation Dosimetry"

"President's Report to the General Assembly of IRPA," Brighton, England, May 1970, Health Physics, Vol. 20, No. 5, 1971

"History of Radiation Protection," Symposium Commemorating the 75th Anniversary of the Discovery of X-Rays, Milwaukee, November 13-14, 1970; Materials Evaluation, Vol. XXIX, No. 3, March 1971

"Why the 1968 Act for Radiation Control for Health and Safety Is Required," Radiology, Vol. 99, No. 3, pages 569-588, June 1971

"Excessive Medical Diagnostic Exposure," Third Annual National Conf. on Radiation Control, Scottsdale, Arizona, May 3, 1971; Published in Proceedings

"Health Physics and the Environment," International Symposium on Rapid Methods for Measurement of Radioactivity in the Environment, Neuherberg, Federal Republic of Germany, IAEA-STI/PUB/289, Vienna, 1971

"Adequacy of Present Radiation Standards," presented at the Environmental and Ecological Forum, Silver Spring, Maryland, January 20, 1971; Proceedings of Forum published in 1972, USAEC-TID-25857

"Proper Use of Information on Organ and Body Burdens of Radioactive Material," presented at the IAEA/WHO Symposium on the Assessment of Radioactive Organ and Body Burdens, Stockholm, Sweden, November 22-26, 1971, IAEA/SM/150-50; Proceedings of Symposium published by IAEA

"Health Physics Measures to Implement New USAEC Regulations Relating to Radiation Exposure of the General Public," Budapest, May 1971; Proceedings published by Akademiai Kiado, Budapest, Hungary

"The Need to Reduce Medical Exposure in the United States," outline of testimony presented before the Health and Welfare Subcommittee of the Senate Committee on Labor and Public Welfare on Senate Bill S.3327, May 15, 1972, Washington, D. C.; published in Congressional Record, 1972

"Comparison of Radiation Exposure of the Population from Medical Diagnosis and the Nuclear Energy Industry," Transactions ANS, 15:1, 64 (June 1972)

"Environmental Impact of Natural and Man-Made Ionizing and Non-Ionizing Radiations," Second International Summer School on Radiation Protection, Herceg Novi, Yugoslavia, Aug. 1973; Proceedings, 1973

"The Need for Radiation Protection," Radiologic Technology, 44, 6, p. 385 (1973)

"Exposure in the United States," and "Mogliche Folgen einer Ubermassigen Medizinischen Strahlenbelastung in der Vereinigten Staaten von Amerika," Rontgen-Blatter, 27, 127 (March 1974)

"Reducing Medical Exposure to Ionizing Radiation," American Industrial Hygiene Journal (May 1975).

Two chapters in text, Environmental Problems in Medicine titled "Exposure to Non-Ionizing Radiation" and "Ionizing Radiation Exposure," W. D. McKee, Editor; Chas. C. Thomas Publisher, 1974

"Types of Environmental Health Physics Data That Should Be Collected and Evaluated in a Nuclear Power Program" in Environmental Impact Statements for Nuclear Power Plants, 1975, Pergamon Press

Chapters by K. Z. Morgan in test, Environmental Impact of Nuclear Power Plants, by R. A. Karam and K. Z. Morgan, GEORGIA INSTITUTE OF TECHNOLOGY SERIES IN NUCLEAR ENGINEERING, Pergamon Press 1975

"The Bases for Standards and Regulations" in Environmental Impact Statements for Nuclear Power Plants, 1975 Pergamon Press

Chapters by K.Z. Morgan in text, Environmental Impact of Nuclear Power Plants, by R. A. Karam and K. Z. Morgan, GEORGIA INSTITUTE OF TECHNOLOGY SERIES IN NUCLEAR ENGINEERING, Pergamon Press 1975

"Release of Radioactive Materials from Reactors" and "Ways of Reducing Radiation Exposure in a Future Nuclear Power Economy," in Nuclear Power Safety, GEORGIA INSTITUTE OF TECHNOLOGY SERIES IN NUCLEAR ENERGY, Pergamon Press

"Transportation of Radioactive Material by Passenger Aircraft," Report to Joint Committee of Congress on Atomic Energy, Report No. 1 - Sept. 17, 1974, U. S. Government Printing Office

"Health Physics -- Past, Present and Future," presented at First Asian Regional Congress of the International Radiation Protection Assn. in Bombay, India, Dec. 1974; published in Proceedings

"Suggested Reduction of Permissible Exposure to Plutonium and Other Transuranium Elements," J. Am. Ind. Hygiene 36 (8), 567 (Aug. 1975)

"Effects of Radiation on Man -- Now and in the Future," in Energy and the Environment -- Cost-Benefit Analysis; Pergamon Press, 1976,

Chapters by K. Z. Morgan in text, Energy and the Environment, Cost Benefit Analysis, by R. A. Karam and K. Z. Morgan, GEORGIA INSTITUTE OF TECHNOLOGY SERIES IN NUCLEAR ENGINEERING, Pergamon Press 1976

"Programs Needed for Education and Training of Health Physicists," Proc. Am. Phys. Soc. Meeting, December 1974

"Recent Developments in Fast Neutron Personnel Dosimetry Using Track Etch Methods," presented at Congress of the International Radiation Protection Assn., Holland, May 1975; published in Proceedings

"Medical Radiation Protection," presented at Health Physics Society Meeting, Buffalo, New York, July 15, 1975

"Ways of Reducing Exposure in a Future Nuclear Power Economy," presented at American Public Health Association Annual Meeting, Chicago, Illinois, November 18, 1975

"A Course on Non-Ionizing Radiation Protection for State and Local Health Officers," Proceedings of Health Physics Society, Denver, Colorado, February, 1976

"The Particle Problem," Third International Summer School on Radiation Protection, Herceg Novi, Yugoslavia, published in Boris Kidric Institute Series, August-September 1976

"The Linear vs. The Threshold Hypothesis," Third International Summer School on Radiation Protection, Herceg Novi, Yugoslavia, published in Boris Kidric Institute Series, August-September, 1976

"Current Problems and Concepts of the Health Physicist," Third International Summer School on Radiation Protection, Herceg Novi, Yugoslavia, published in Boris Kidric Institute Series, August-September 1976

"Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," testimony presented at public hearings on MOX fuel, Washington, D.C., Nov. 1976

"Keeping Dose Commitments ALAP," Proc. ANS National Topical Meeting, 71, Tucson, Arizona, October 6-8, 1975

"Radiation-Induced Health Effects," Science 195, 157, 344 (January 28, 1977)

"The Dilemma of Present Nuclear Power Programs," Proc. of Hearings Before the Energy Resources Conservation and Development Comm., Sacramento, Cal., February 1, 1977

"Comments on Operation of the Kerr-McGee Cimarron Facility and the Karen Silkwood Case," before the Congressional Small Business Comm., April 26, 1976

"Data Interpretation," Proceedings of Workshop on the Utilization and Interpretation of Environmental Radiation Data, Orlando, Fla., March 1-3, 1976

"Rolf M. Sievert: The Pioneer in the Field of Radiation Protection," Health Phys. 31, 263-264 Sept. 1976

"Health Hazards from Diagnostic and Therapeutic X-Ray," Proceedings of Conference on Diagnostic Imaging, Chicago, Ill., Sept. 27, 1976

"Yes is the Answer to Question of R. H. Thomas and D. D. Busick, 'Is It Really Necessary to Reduce Patient Exposure?'" J. Am. Ind. Hygiene 37, 665-667, Nov. 1976

"The Linear Hypothesis of Radiation Damage Appears to Be Non-Conservative in Many Cases," Proceedings of Fourth International Congress of the International Radiation Protection Association, Paris, France, April 25-29, 1977.

"The Need to Reduce Medical Diagnostic Exposure," J. Am. Ind. Hygiene 38, 6, June 1977.

"Possible Consequences of Excessive Medical Exposure in the United States," Given before the Fachverband fur Strahlenschutz at the Bern, Switzerland meeting, March 21, 1973 and published in the Fachverband Proceedings, 1973.

"Biological Effects of Ionizing Radiation," published in Proceedings of Short Course, September 9, 1974.

"Appropriateness of Regulations for Air Shipment of Radioactive Materials," Miami Beach, Florida, September 23, 1974, International Conference on Shipping of Radioactive Material; and published in Proceedings, 1975.

"Recent Developments in Fast Neutron Personnel Dosimetry Using Track Etch Methods," Proc. 3rd European Congress IRPA, Paper 14, Amsterdam, The Netherlands, May 1975, with Mehdi Sohrabi.

"Development and Application of Some Fast Neutron Dosimetry Techniques Utilizing Plastic Track Detectors for Radiotherapy and Health Physics," USERDA Contract No. AT-(40-1)-4814, 1975, with Mehdi Sohrabi.

## Biographical Sketch

SU, SHIAN-JANG--Ph.D. Candidate, Georgia Institute of Technology, School of Nuclear Engineering

### Education

| | |
|---|---|
| B.S., Nuclear Engineering, National Tsing Hua University | 1968 |
| M.S., Nuclear Science, National Tsing Hua University | 1970 |
| Ph.D. Candidate, Georgia Institute of Technology | 1975-Present |

### Employment History

| | |
|---|---|
| Atomic Energy Council, Republic of China, Research Assistant | 1968 |
| Army of Republic of China, 2nd Lieutenant | 1970-1971 |
| Institute of Nuclear Energy Research, Researcher | 1971-1975 |
| Karshrue Nuclear Center, West Germany, Practical Training | 1972 |
| Georgia Institute of Technology, Graduate Assistant | 1976-Present |

### Experience Summary

While working at the Institute of Nuclear Energy Research, Republic of China, Mr. Su was responsible for radiation dosimetry in the health physics section. He attended many programs such as construction of whole body counters, hot cell shielding design, personnel monitoring and instrument calibration for a 50 MW heavy water reactor and radioisotope applications. In July 1972, under the sponsorship of the Atomic Energy Council, Mr. Su went to West Germany and attended practical training at the WAK fuel reprocessing plant. Since 1975 he has been pursuing a Ph.D. degree in Nuclear Engineering with a specialty in Health Physics. He is a member of the China Nuclear Society and the Health Physics Society.

### Reports, Publications and Papers

1. B.S. Thesis, "Fast Neutron Flux Measurement of 1MW Tsing Hua Open Pool Reactor," National Tsing Hua University, 1968.
2. M.S. Thesis, "Study on Taiwan Natural Background," National Tsing Hua University, 1970.
3. Su, Shian-Jang, "A Preliminary Calculation of Argon-41 Gamma Dose From TRR," Nuclear Science Journal, 11, 58 (1974).
4. Su, Shian-Jang, "Final Report for Whole Body Counter," INER, Taiwan (1975).
5. Su, Shian-Jang, "Neutron Dosimetry Using Electrochemical Etching," Paper presented in 1977 American Nuclear Society Eastern Region Student Conference, Raleigh, N. C., 1977.
6. Literature review of the proposed research, "Neutron Dosimetry Using Electrochemical Etching," in partial fulfillment of the Ph.D. degree, Georgia Institute of Technology, 1977.
7. Su, Shian-Jang, "Neutron dosimetry using Electrochemical Etching," Paper P/21 presented in 22nd Annual Meeting of the Health Physics Society, Atlanta, Georgia, 1977.
8. Su, Shian-Jang, "Detection of Hot Fallout on Taiwan in the Period 1971-1975," Health Physics, 33, 241 (1977).

## New Graduate Students Assigned to Project

Dorothy Rea graduated with the B.S. degree from Virginia Polytechnic Institute and State University in 1977 with a major in Biology and is enrolled in the graduate program of the School of Nuclear Engineering of Georgia Institute of Technology beginning in September 1978.

Michael Edmond Sanders took a number of courses at Ohio State University and completed his B.S. program at Oklahoma State University in 1977 with a major in Radiation Technology. He will enter the graduate program of the School of Nuclear Engineering of Georgia Institute of Technology in September 1978.

## GEORGIA TECH FACILITIES

The facilities most closely related to teaching and research in the nuclear engineering programs at Georgia Tech are located in the Frank H. Neely Nuclear Research Center and the Cherry L Emerson Building.

### Nuclear Research Center

The Frank H. Neely Nuclear Research Center, valued at $10 million dollars, was completed in 1964. The Georgia Tech Research Reactor (GTRR) which serves as the key component to the Center is a heterogeneous, heavy-water moderated and cooled reactor, fueled with enriched uranium. It is similar in design to the Argonne Research Reactor, CP-5, which has demonstrated excellent research capability and dependable service. The GTRR has been designed to develop a sustained power output of five megawatts with a corresponding thermal neutron flux of about $10^{14}$n/cm$^2$-sec. The reactor has a variety of experimental facilities (such as beam tubes, through-tubes, pneumatic tubes, fast flux facility, biomedical facility, thermal column, and gamma facility) to provide a wide range of experiments. The GTRR currently operates at a power of five megawatts two or three shifts per day.

The reactor and associated systems are housed in a steel containment building eighty feet in diameter and sixty-five feet in height. The adjoining 24,000 square foot, two-story, air-conditioned laboratory and office building contains laboratories for radiochemistry, health physics, materials preparation, nuclear spectroscopy, low-level counting, radiobiology, electronics, as well as a machine shop and a large animal quarter.

Equipment at the Frank H. Neely Nuclear Research Center includes:

5 megawatt, heavy-water research reactor

Neutron diffractometers (3)

Time-of-flight neutron spectrometer

Experimental setup for pile oscillator measurements

100,000 curie $Co^{60}$ facility

50,000 curie capacity hot cell with master-slave manipulators

20' x 6' x 18' deep storage pool joined to hot cell by transfer chute

Neutron generator--200 keV TMC Activation Model 211, (d,n) reactor with tritium producing 2 x $10^{14}$ MeV neutrons/sec

Gamma facility--spent fuel element storage in pool provides gamma rates to $10^{6}$ R/hr depending on sample geometry

Intermediate level radiochemistry laboratory (18' x 26') with radioisotope hoods, shielded glove boxes

Facilities for treatment, storage, and handling of solid and liquid radioactive wastes, including retention tanks of 8000 gallon capacity

Model 33 teletype terminal providing remote computer access on and off campus

Data acquisition system

The data acquisition system consists of three data processors (PDP-8, PDP-8/I, and PDP-12), with appropriate peripheral devices for use in sophisticated experiments requiring on-line analysis and control, as well as data collection. One of the processors is located within the reactor containment building and is intended for use by experimenters with a minimum of setup time. A rather sophisticated interface for accepting both digital and analog signals is operational. There is a communications link to the other processors, located in the laboratory portion of the Center, which acts as

a data collection center for several experiments and a secondary processor. Cell processors function (with lower priority) as a data reduction and preprocessing facility, and as such are generally available for use 24 hours per day.

## Emerson Building

The School of Nuclear Engineering also occupies about 24,000 square feet in the Cherry L. Emerson Building. This space contains ample classrooms, student laboratories and offices as well as a periodical library, staff machine shop, electronics shop, seminar room, computation laboratory and a large, two-story high bay with 10 ton crane. The latter space houses the nuclear engineering laboratory. The counting rooms and other laboratories have been well equipped with conventional radiation detection instruments (including several multichannel analyzers) in sufficient numbers to accommodate laboratory sections of 12-15 graduate students.

Specialized equipment available in the Emerson Building to nuclear engineering students includes:

An AGN-201 training reactor

A natural uranium-light water subcritical assembly

Korad K-15 pulsed ruby laser

Three EAI model TR-20 analog computers

A 12,000 curie Cs-137 gamma source

One MeV Van de Graaff positive particle accelerator with beam analysis system

50 and 250 KVP x-ray machines

Several gas chromatographs

Eleven radioisotope fume hoods and three glove boxes

Vacuum deposition system

The training reactor is located in the nuclear engineering laboratory. It is used in laboratory exercises and for special student problems and theses. The GTRR continues to be available for all pedagogical experiments and research which require its higher flux.

## Rich Electronic Computer Center

The Georgia Tech Rich Electronic Computer Center was established in 1955 and its facilities are an integral part of the academic and research programs at Georgia Tech. The Office of Computing Services operates two large-scale digital computers, a Control Data Corporation CYBER 74 system and a Control Data Corporation 6400 system. Both systems operate under the NOS 1.0 operating system, thus providing back-up capabilities.

The CDC CYBER 74 has the following configuration: Two central processors (one 6400 and one 6600), fourteen peripheral processors, 131,072 words of core memory (60 bit words), 944 million characters of disk storage, eight magnetic tape drives, two card readers (1200 cpm), three line printers (1200 lpm), one card punch (250 cpm), 64 ports for time-sharing users, and an operator console. A CALCOMP Model 763 Digital Incremental Plotter provides high quality.

The following software packages are available: COMPASS, ALGOL, COBOL, FORTRAN (four different compliers are available), APL, RPG, MIMIC, MIX, plus many others.

A Radiation, Inc. Analog-to-Digital conversion system is available in an off-line mode. It multiplexes up to 16 channels of analog magnetic tape input in a sequence determined by a programmable scanner, digitizes the samples at a rate up to 50,000 amples per second and to an accuracy of 11 bits plus sign, and produces a digital magnetic tape output.

## Small Computer Applications Laboratory

The Small Computer Applications Laboratory was established to provide expertise for the development of complete hardware-software systems, particularly those systems associated with nuclear instrumentation and data reduction.

The laboratory has both general-purpose and specialized facilities for the application of small computer systems to a wide variety of research, development, instrumentation, and educational areas. It is equipped with four general purpose computers (a PDP-12, PDP-8/I, GT 42, and PDP-8) with various peripheral equipment specifically suited to small computer applications and system development. The 8K PDP-12 with its high speed disk storage, line-tape storage, and a graphics facility plays an important role in software systems development and data storage. In addition, the PDP-12 is equipped with multiple analog-to-digital converters, relays, a programmable KW-12A clock, and an I/O access panel to provide convenient development, fabrication, testing, and simulation of the interfacing of special equipment to the computer.

## Library

The Price Gilbert Memorial Library is a centralized scientific, technical, and management collection of 730,000 volumes, plus 690,000

microtext and other bibliographic units. Outstanding collections in the fields of science and engineering have been developed to support graduate study and research. It is housed in adjoining structures totaling 240,000 square feet of space. It can house over one million volumes and can seat two thousand users. The library's United States Patent specification collection is the only one in the Southeastern area. In 1962, the library was designated one of twelve Federal Scientific Report Centers and its collection of reports from the Atomic Energy Commission, the Department of Defense, the National Aeronautics and Space Administration, the Clearinghouse for Scientific and Technical Information now totals over 500,000 titles. Extensive files of standards issued by American associations and societies and a complete file of U.S. Military Standards and Specifications and of British Standards are maintained. The library is also a depository for United States government publications issued by the Government Printing Office, and for maps issued by the Army Map Service. Available on microfilm are more than 6,000 company catalogs providing information on industrial components.

## Other Facilities

Georgia Tech has many other facilities closely allied with the nuclear engineering program including, for example, various facilities operated by Divisions of the Engineering Experiment Station. Among these are specialized laboratories utilizing x-ray equipment, optical and electron microscopes, emission and absorption spectroscopes, analog computers, microwave systems, cryostats and many other research devices. In addition, close cooperation exists between the School of Nuclear Engineering and other Schools of the Engineering College and the School of Physics.

# DEVELOPMENT AND APPLICATION OF THE ELECTROCHEMICAL ETCHING TECHNIQUE

Annual Progress Report

(Contract No. EY-76-S-05-4814)

August, 1978

School of Nuclear Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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Summary

Further studies are reported on the development and application of charged particle track amplification in polycarbonate foils by electrochemical etching for fast and thermal neutron dosimetry as well as alpha particle dosimetry which have been carried out since our August, 1977 Progress Report. Results obtained thus far in the long term goal of determining the average dose delivered to the endosteal tissue of bone by $^{239}Pu$ alpha particles are reported. Some of the initial work has been involved in calibrating this dosimeter for alpha particles, i.e. finding the efficiency of alpha particle track production and the track diameter as a function of etching time. Progress will be indicated also in the actual bone dosimetry work using the bone samples we have obtained from Dr. B. D. Breitenstein from Hanford and Dr. W. S. S. Jee from the University of Utah. Since our last progress report, additional results have been obtained concerning the energy dependence of these foils with respect to recoil particle track registration from fast neutrons. Initial results are also presented in our new effort to use these foils for the purpose of thermal neutron dosimetry. This latter study has just been initiated and involves the use of $^{6}Li$ to interact with thermal neutrons in the (n, $\alpha$) reaction ($\sigma_c \approx 953b$). The alpha particle resulting from this reaction can thus create tracks in the foils. One member of this research group (Stillwagon) spent ten days working with Dr. Webster Jee and his group at the University of Utah studying deposition of actinide elements in the endosteum of bone of dogs and found this a most profitable (and hopefully, mutually valuable) exchange

of information. Thus far during the course of this research, papers were presented at student conferences of the American Nuclear Society at the University of North Carolina (Raleigh) and the University of Florida (Gainesville) as well as the annual meeting of the Health Physics Society in Atlanta and Minneapolis, Minnesota - reprints are attached to this report.

## Introduction

This is our final Progress Report on further development and application of charged particle track formation in polymers such as polycarbonate amplified by electrochemical etching for fast neutron and alpha particle dosimetry. Also, this Report is accompanied by a Renewal Proposal in the hope that these interesting and productive studies can be continued in order to follow up on some promising developments discussed in this report. Briefly, the electrochemical etching technique involves irradiation of a sensitive polymer by either charged particles, such as protons and alpha particles, or fast neutrons followed by an electrochemical etching treatment to reveal the induced recoil, (n, C), proton or alpha particle tracks. Electrochemical etching proposed by Tommasino,[1] when applied to recoil particle tracks overcomes many shortcomings of conventional etching methods leading to a new and more sensitive avenue in fast neutron dosimetry (Sohrabi).[2,3] The same is true also of using the electrochemical etching of polycarbonate foils for alpha particle dosimetric purposes over the more commonly used photographic emulsions. The results of studies designed to determine the parameters needed to use this dosimeter for alpha particle dosimetry are presented here and elsewhere (Stillwagon and Morgan).[4] The main thrust of this area of our research is to determine the average dose delivered to the layer of tissue 10 μm removed from the endosteal surface of bone by $^{239}Pu$ alpha particles (Stillwagon, et al).[5,6] Thus, for the first time it may become possible

to calculate the maximum permissible organ burden (MPOB) of $^{239}Pu$ by the proper method as recommended by the International Commission on Radiological Protection (ICRP). The other major area of our work deals with fast and thermal neutrons (Su, et al).[7] Results will be presented here concerning the energy dependence and threshold for track production in these polycarbonate foils. The results of our study to determine not only the fast neutron dose but also the thermal neutron dose using our technique will be presented.

Past results concerning fast neutron sensitivity and physiochemical characteristics of this approach are now available in the literature by Sohrabi and Morgan.[8-12] The results are all in favor of supporting and using this technique for a number of applications in health physics, radiotherapy and radiography. Some of the results were reported in previous progress reports from our laboratory and other publications, some in this report and some will be studied during the remaining contract period. This report covers the progress from our August, 1977 Progress Report through the present. Results of current studies as reported here are divided into two main categories and five sub-categories:

1. Alpha Particle Dosimetry Studies
   a) Bone dosimetry
   b) Efficiency of alpha particle track formation
   c) Track diameter as a function of etching time

2. Neutron Dosimetry - Fast and Thermal
   a) Energy dependence of dosimeter response
   b) Thermal neutron dosimetry

# I. Alpha Particle Dosimetry Studies

## A. Bone Dosimetry

The effects of alpha particle irradiation realized in tissue can be quite severe indeed, even at a fairly low, macroscopically calculated dose. Carcinoma involving epithelial cells (cells of the sinus cavity and surrounding bone), pulmonary neoplasia, fibrosis, necrosis, spontaneous bone fractures, tooth and tooth socket effects, osteomyelitus, osteoporosis, osteosarcoma, hemorrhage, edema and even leukemia are all possible results of alpha irradiation in vivo. Death can be caused by an average skeletal dose of only 60 rads (Mays and Lloyd)[13] in beagles when injected with $^{239}Pu$ citrate intravenously of 90 rads in humans injected with a $^{224}Ra$ solution (Speiss and Mays),[14] or by an average skeletal dose of 1200 rads in humans ingesting $^{226}Ra$ (Evans, et al).[15] The primary concern here is the nuclide $^{239}Pu$.

The public today is becoming increasingly disturbed over the nuclide $^{239}Pu$ which is utilized in the nuclear industry. $^{239}Pu$ is produced in great quantities in $^{235}U$ - $^{238}U$ fueled reactors so potential exposure to man will be present during the handling of spent fuel during reprocessing or prior to disposal. Also $^{239}Pu$ is produced for use in weapons and the production of these weapons presents a possible source of human exposure. Lastly, due to weapons tests in the atmosphere, approximately 300 kCi of $^{239}Pu$ have been released worldwide. In addition to the availability of $^{239}Pu$, the great toxicity of $^{239}Pu$ is probably one of the major reasons for interest in this nuclide. It is known from work by Jee, Thompson, Bair, Mays, and others[13,17-41] that

microgram quantities of $^{239}Pu$ administered to experimental animals by various methods are capable of producing lethality in these animals. It should be mentioned here also that although primary reference is made in this study of $^{239}Pu$, it is seldom the pure radioisotope. $^{239}Pu$ is present and in the practical case, e.g. environmental contamination and nuclear reactor operations, the Pu is some mixture of $^{238}Pu$, $^{239}Pu$, $^{240}Pu$, $^{241}Pu$, and $^{242}Pu$. However, on a curie basis much of what applies to $^{239}Pu$ applies also to the common isotopic mixtures.

Plutonium, like all other actinide elements, radium and strontium, is basically a bone seeker. Although the distribution of $^{239}Pu$ found in the body is dynamic, at any one point in time it will be determined by such factors as route of entry into the body, physical and chemical form, and chemical state of the plutonium, species of the animal, the animals age and general state of health (Jee),[18], etc. When dealing with particulate $^{239}Pu$, the particle size distribution and method of creating the particles is important (Bair).[31] Studies by Hamilton and Durbin [42-49] at the University of California and Jee, Mays, and others[18,19] at the University of Utah using the intravenous mode of administration have shown that a hydrolyzable, polymeric plutonium compound will be taken up preferentially by the liver but a monomeric plutonium compound will be preferentially concentrated by the bone. Unlike other bone seekers such as radium and strontium, plutonium distributes in the bone in a highly uneven manner. Plutonium tends to concentrate on the surfaces of osseous tissue, Fig. 1,[50] and therefore is called a surface seeker. The distribution is not homogeneous with respect to this surface distribution. Plutonium is retained preferentially on the endosteal with an endosteal to periosteal concentration equal to

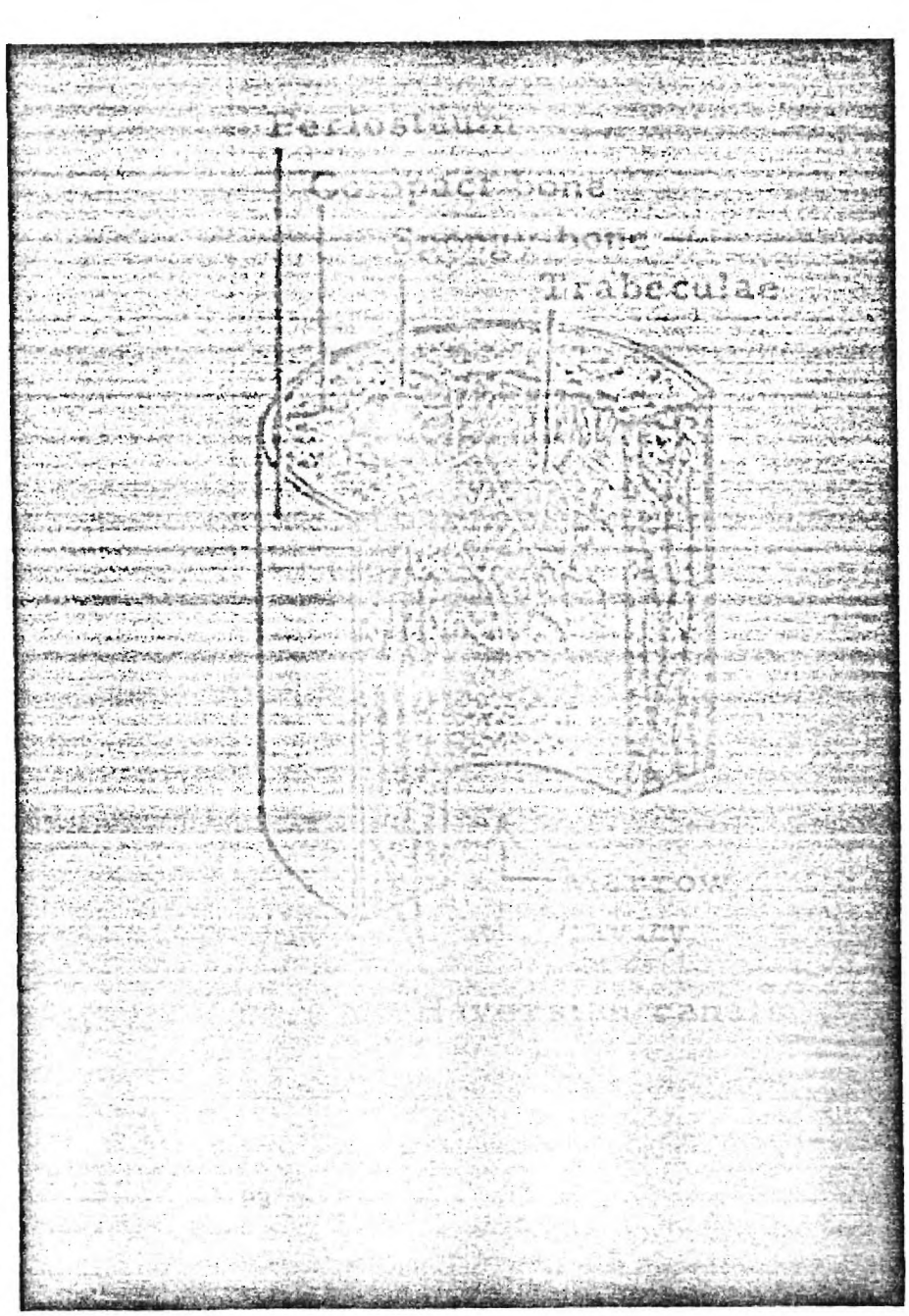


**Figure 1.** Cutaway of the shaft portion of bone showing the location of the periosteal and endosteal surfaces.

about 4 to 1 (Jee).[18] Once deposited, the plutonium essentially remains in place except for very slow removal either by resorption or apposition. This surface deposition has been verified by detailed autoradiographs which show clearly this distribution, Fig. 2.[51] The cells concerned with bone resorption, osteoclasts, progressively concentrate $^{239}Pu$. This plutonium is later relocated to macrophages (as osteoclasts are removed) which travel throughout the marrow irradiating the marrow and the endosteal surface or the $^{239}Pu$ can be recycled into the blood (Durbin),[45] (Jee).[18] The most sensitive gauge of $^{239}Pu$ hazard to mammals is osteosarcoma or bone tumor. Only 3.6 rads delivered to the whole skeleton of a rat was sufficient to cause a tumor (Jee).[18] The risk of tumor formation appears to be related to three factors: (1) the volume of cells at risk from the emitted alpha particle, which is determined by its range, (2) the amount of alpha irradiation impinging upon the bone surface, and (3) the proliferative potential of the cells under irradiation (ICRP).[52]

The ICRP recommends the limiting dose rate to the bone surfaces be set at 15 rem/yr out to a distance 10 μm removed from these surfaces (ICRP).[52] Unfortunately, however, the direct experimental data allowing this recommended limit to be implemented are not available. As a consequence, the old value of the maximum permissible organ burden (MPOB) for $^{239}Pu$ (i.e. 0.04 μCi based on an assumed uniform distribution of $^{239}Pu$ in bone) is still in use both nationally and internationally. It is this inability to apply the dose calculation method urged by ICRP that adds particular importance to this research which


Figure 2. Detailed neutron-induced autoradiograph of portions of four trabeculae, showing fission fragment tracks distributed mostly upon surfaces in the lumbar vertebral body. Bones are from a dog injected with 0.0158μC of $^{239}Pu$/kg Pu(IV) citrate and sacrificed five days later. B denotes bone, M denotes marrow and A denotes buried $^{239}Pu$ (x210).

hopefully, may enable one to properly calculate the MPOB for $^{239}Pu$.

We are presently applying our dosimetry system developed by Sohrabi and Morgan[8] to this dosimetric problem and the details of this usage for the polycarbonate system will be given in the next section. Thus far we have been concerned with evaluation of the parameters needed to apply this dosimeter for bone dosimetry. The parameters include efficiency of alpha particle track production as a function of absorber thickness, track diameter as a function of etching time, and sensitivity as a function of etching time for the maximum efficiency of track production. Another area of endeavor is a study to examine ways of increasing the sensitivity of this dosimeter to alpha particles. We have obtained, mounted, and we are presently exposing bone samples on polycarbonate foils concurrently with the above studies. A more detailed description of the work performed follows in the next two sections and the final results of this research will be reported when the dosimetry of the bone samples is completed.

## B. Efficiency of Alpha Particle Track Formation

The present maximum permissible body burden for $^{239}Pu$, 0.04 μCi (ICRP),[53] was calculated by assuming the $^{239}Pu$ to be homogeneously distributed in the critical organ (bone) for plutonium then applying a weighting factor to allow for the known and unknown inhomogeneities in the osseous distribution of $^{239}Pu$. This inhomogeneity in osseous distribution of plutonium has been known for some time (Scott, et al),[48] (Twente and Jee),[17] but not in a quantitative way such that the method

of dose calculation for $^{239}Pu$ as recommended by ICRP could be applied. The plutonium tends to concentrate on the surfaces of bone, in particular the endosteal surface, and hence, is sometimes referred to as a "surface seeker." This distribution causes the radiosensitive osteogenic cells found lying along the endosteal surface of osseous tissue to be within range of the $^{239}Pu$ alpha particles to a greater extent than if the same amount of plutonium were distributed in a more homogeneous fashion. Realizing this situation, the ICRP requested data giving the dose delivered to the layer of tissue 0-10 μm removed from the endosteal surface of bone from $^{239}Pu$ alpha particles. Such data would be used to determine a value for the MPOB that more accurately and realistically reflects physical fact. There have also been other requests for better internal dosimetry of $^{239}Pu$ (Natural Science Group).[54] In an effort to partially fulfill these requests, this study seeks to determine the average dose to the tissue 0-10 μm removed from the endosteal surface of the bone from $^{239}Pu$ (Stillwagon, et al.)[5] The basic technique employed will be to amplify the tracks produced by $^{239}Pu$ alpha particles on polycarbonate foils by electrochemical etching. In order to approach an average dose for alpha particle irradiations we need small, homogeneously distributed tracks placed as close together as possible (Rossi).[55] To make this determination, several parameters need to be evaluated. Two of these have been evaluated and are presented in this and the next section. These parameters are the efficiency of alpha particle track production in polycarbonate foils as a function of absorber thickness and the track diameter as a function of etching time for alpha particle irradiations.

In the process of electrochemical etching a voltage difference is applied across a chamber such as the one in Fig. 3, in an alternating fashion using 250 μm thick polycarbonate foils. The etching equipment is shown in Fig. 4. Visible are the audio frequency generator, amplifier, etching chamber, and voltmeter. To examine the efficiency of alpha particle track production, a device called the vacuum-sealed alpha-calibrator was designed and constructed in this research, Fig. 5. This device allows a constant source to detector distance using an isolatable source and exchangeable tops to the chamber, one for the surface barrier detector and one for the polycarbonate foils. Different absorber thicknesses can be simulated by varying the air pressure in the chamber which is constantly monitored. The source used here was a 2.0 μCi $^{239}Pu$ source. First, various air densities, applying the standard temperature and pressure corrections, were used while irradiating an Ortec surface barrier detector which provided input into a Model 8100 Canberra multichannel analyzer. The total number of alpha particles and peak energies were noted. Then the top made to hold polycarbonate foils was employed and, to ensure similar irradiation conditions, ceramic rings were provided by The Ortec Company identical to the rings utilized in the construction of their surface barrier detectors and placed on the foil at the position formerly occupied by the surface barrier detector. After irradiation at the same air densities, the foils were etched by the above method for four hours in 28% KOH utilizing an applied voltage of 800 V at 2 KHz and 24°C.

The results obtained form this study to determine the efficiency of alpha particle track production as a function of absorber thickness

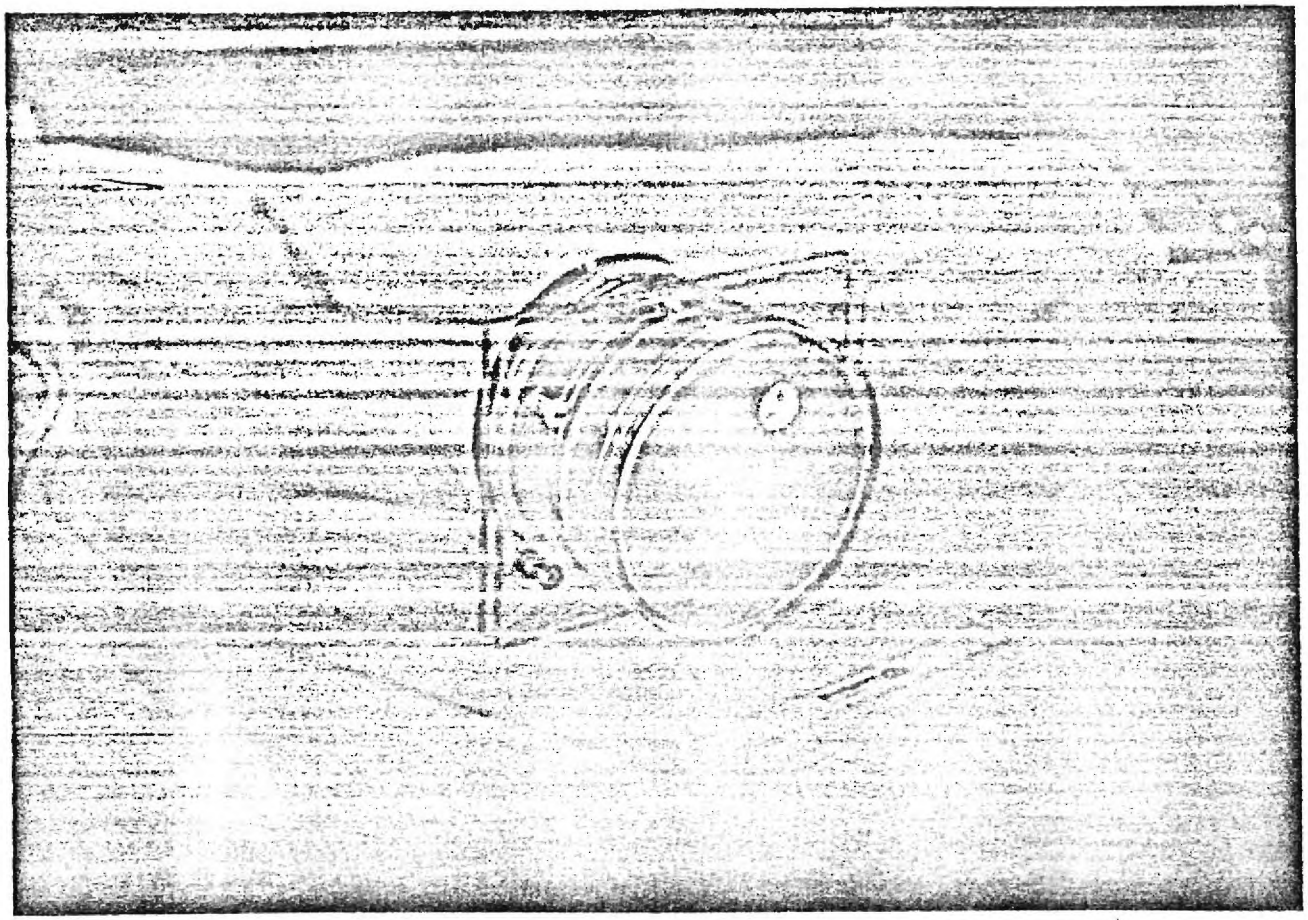

**Figure 3. A Plexiglass etching chamber.**

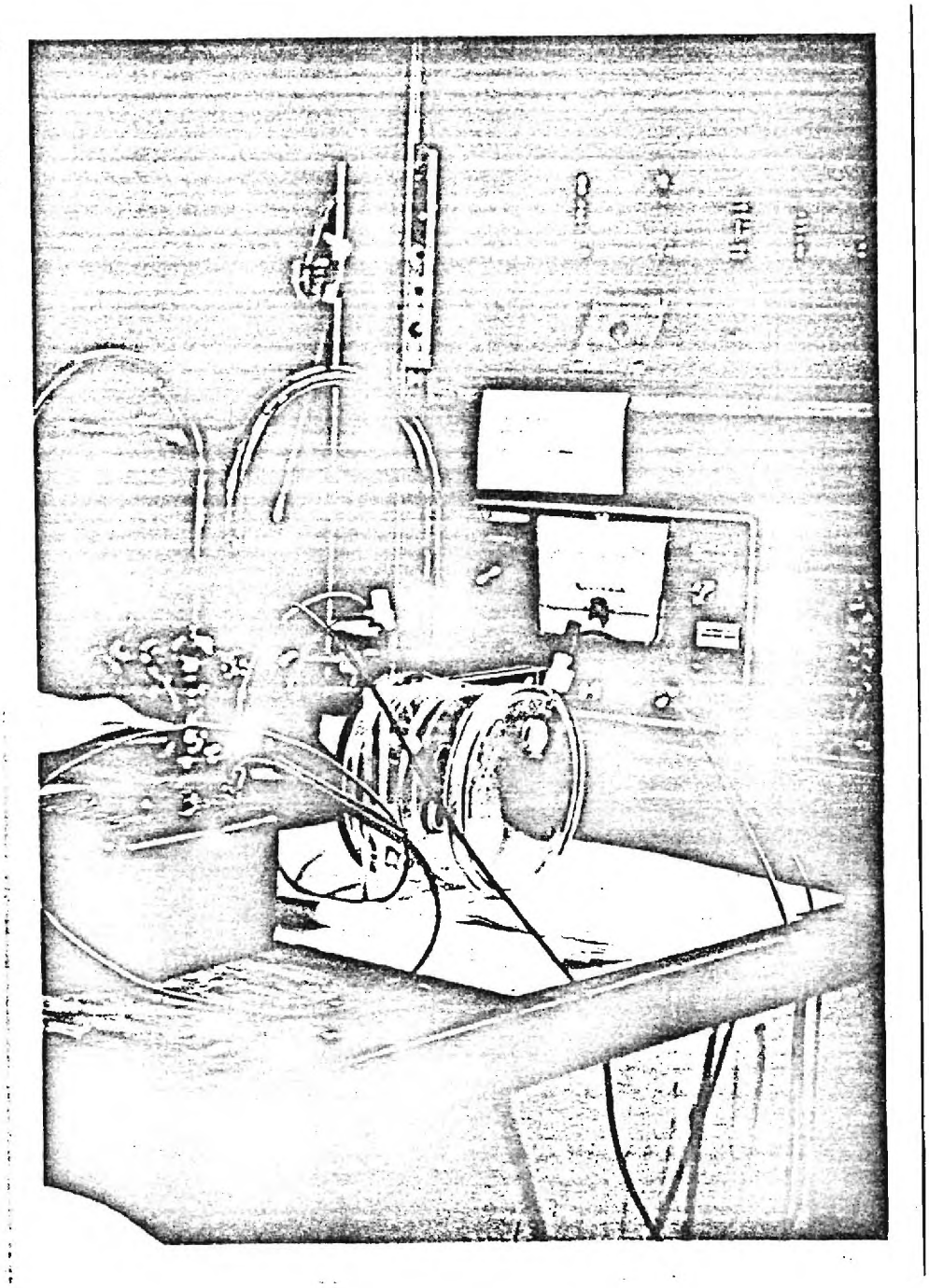

**Figure 4.** Electrochemical etching apparatus showing etching chamber, audio oscillator, amplifier and volt meter.

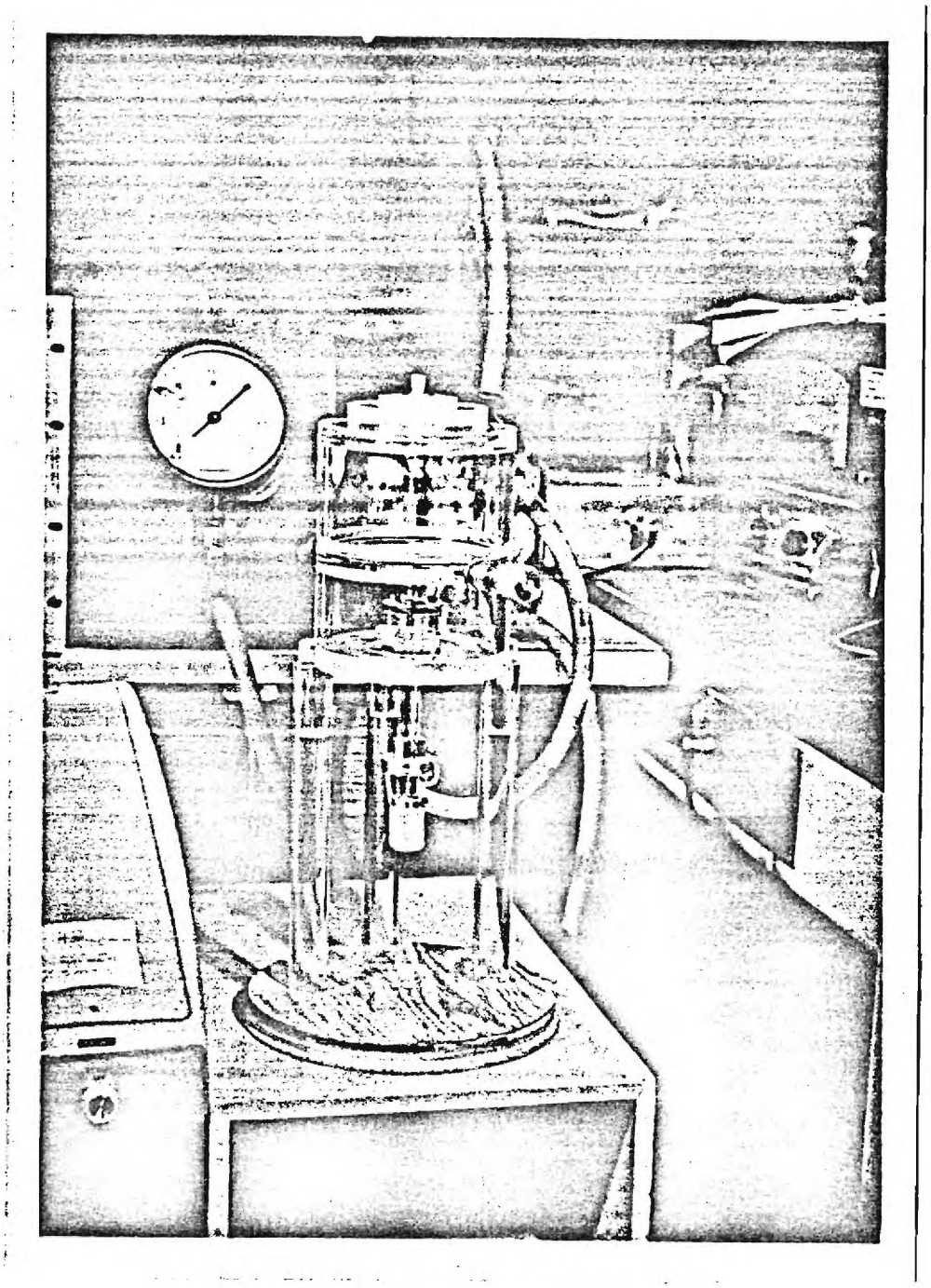

Figure 5. Closeup of the vacuum-sealed alpha calibrator showing the vacuum hookup, two compartment design and the calibrated source stand.

are shown in Fig. 6. Here the number of tracks recorded on the various foils is plotted against the absorber thickness. Fach point on the curve represents the average of more than one foil, usually two or three, and the error bars correspond to one sigma.

Figure 6, showing the efficiency of alpha particle track production as a function of absorber thickness, yielded a clear Bragg curve typical of an alpha particle. The track peak of the curve was slightly more than twice that for the flat portion of the curve. Also, the peak fell off quite sharply down to zero at 34 μm of polycarbonate and again on the left hand side of the peak towards the flat portion of the curve. The x-axis was converted from air density to microns of polycarbonate by the standard conversion.

C. Track Diameter as a Function of Etching Time

To examine the track diameter as a function of etching time, 250 μm thick polycarbonate foils were irradiated by one of three alpha particle sources - two 0.1 μCi $^{241}Am$ sources and one 0.2 μCi mixed nuclide source containing $^{239}Pu$, $^{241}Am$, and $^{244}Cm$. These foils were then etched for varying times between 15 minutes and 4 hours in 45% KOH using an applied voltage of 800 V at 2 KHz and 24°C.

The results of the track diameter versus etching time are plotted in Fig. 7. The graph shows the track diameter plotted against etching time for times ranging from 30 minutes to 4 hours. No tracks were observed for an etching time less than 30 minutes. Each point represents the average of the two extreme values of track diameter falling into each track category observed using a Filar micrometer at 430X power.

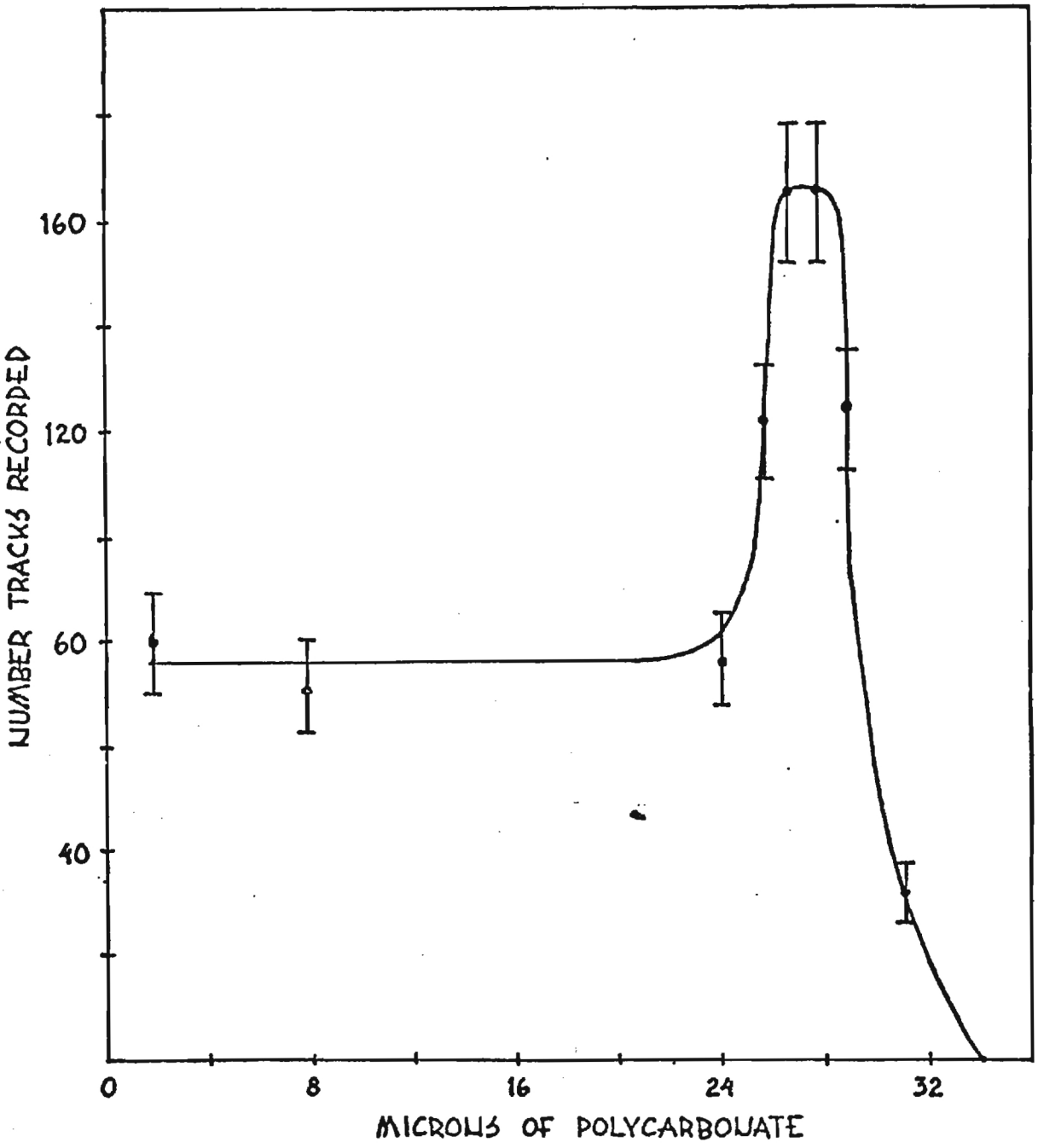


Figure 6. Efficiency of Track Production as a Function of Absorber Thickness. Polycarbonate Absorber Thickness was Calculated from g/cm$^2$ of Air.

The error bars in this case are not true error bars but simply indicate the ranges in values obtained for the track diameter in each case. Two groups of tracks - large and small - were observed in these studies. This was reported in a paper given at the annual meeting of the Health Physics Society (Stillwagon and Morgan)[4] and to our knowledge this is the first time this observation has been reported. A paper reporting this finding is in publication (Stillwagon and Morgan).[4]

The graph in Fig. 7 contains curves for the two groups of tracks. After polycarbonate foils were irradiated by alpha particles, etched by our technique and viewed, there appeared two distinct groups or categories of tracks on the foils, Fig. 8. There were a few large tracks and many small tracks, but as shown in Fig. 9, the number of large tracks decreased and the number of small tracks increased with increasing absorber thickness. To check if this phenomenon of the two categories of tracks was real, the diameters of the tracks on a foil were measured and the relative frequency of the various diameters plotted, Fig. 10. Here the relative frequency, expressed in percent, of the track diameters is plotted in steps of 0.5 μm in histogram fashion. We can plainly see two categories of tracks present on the foil represented graphically by the two large peaks of equal magnitude, one between 3.5 and 4.0 μm and the second between 10.0 and 10.5 μm. In general, no tracks were observed smaller than 3.0 μm and none were observed greater than 115.5 μm throughout these measurements. Four histograms similar to Fig. 10 could be drawn for each foil used to generate the curves shown in Fig. 9. Figures 11 and 12 are sample curves for absorber thicknesses of 27 μm and 2 μm of polycarbonate, respectively. Here, as the absorber

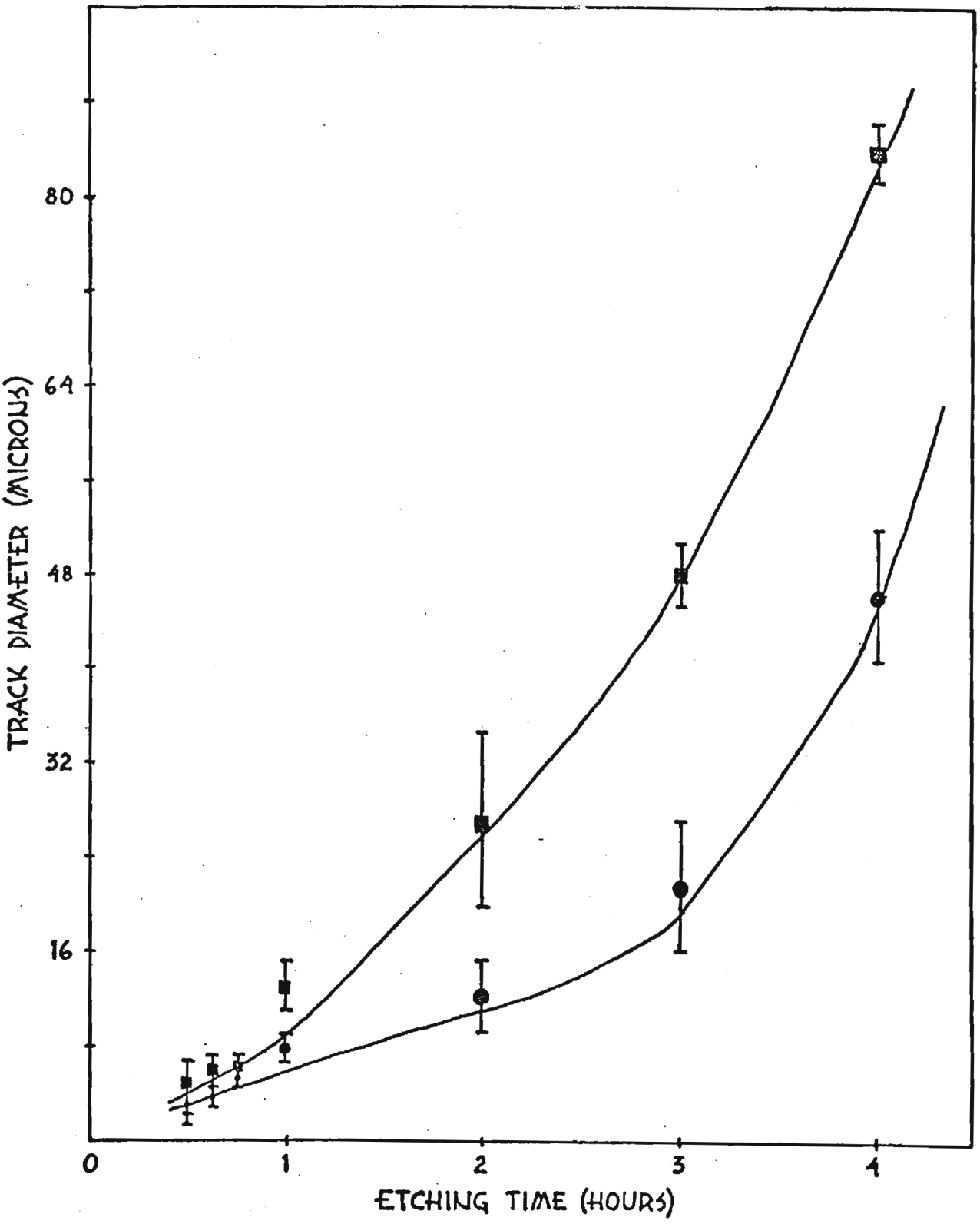


Figure 7. Variation of Track Diameter with Etching Time. Upper Curve is the Large Diameter Tracks, and the Lower Curve is the Smaller Diameter Tracks.

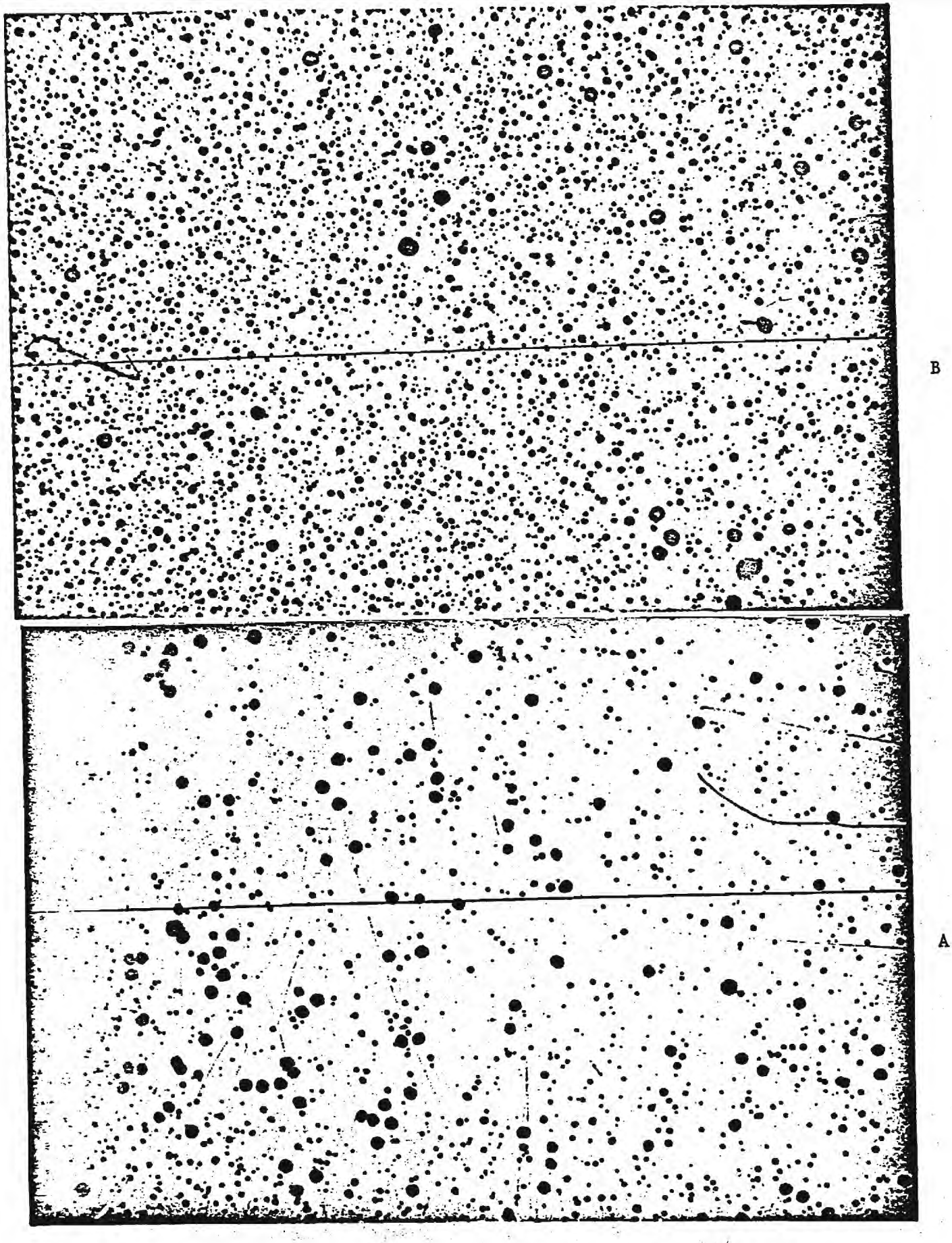


Figure 8. Tracks created by the 5.44 MeV alpha particles of $^{241}Am$ at a source to dosimeter distance of 2 mm in air. Irradiation time = 14 hours. A. Without foil masking. B. With foil masking. Etching parameter- 45% KOH, 800 volts, 2 KHz and etching time 5 hours.

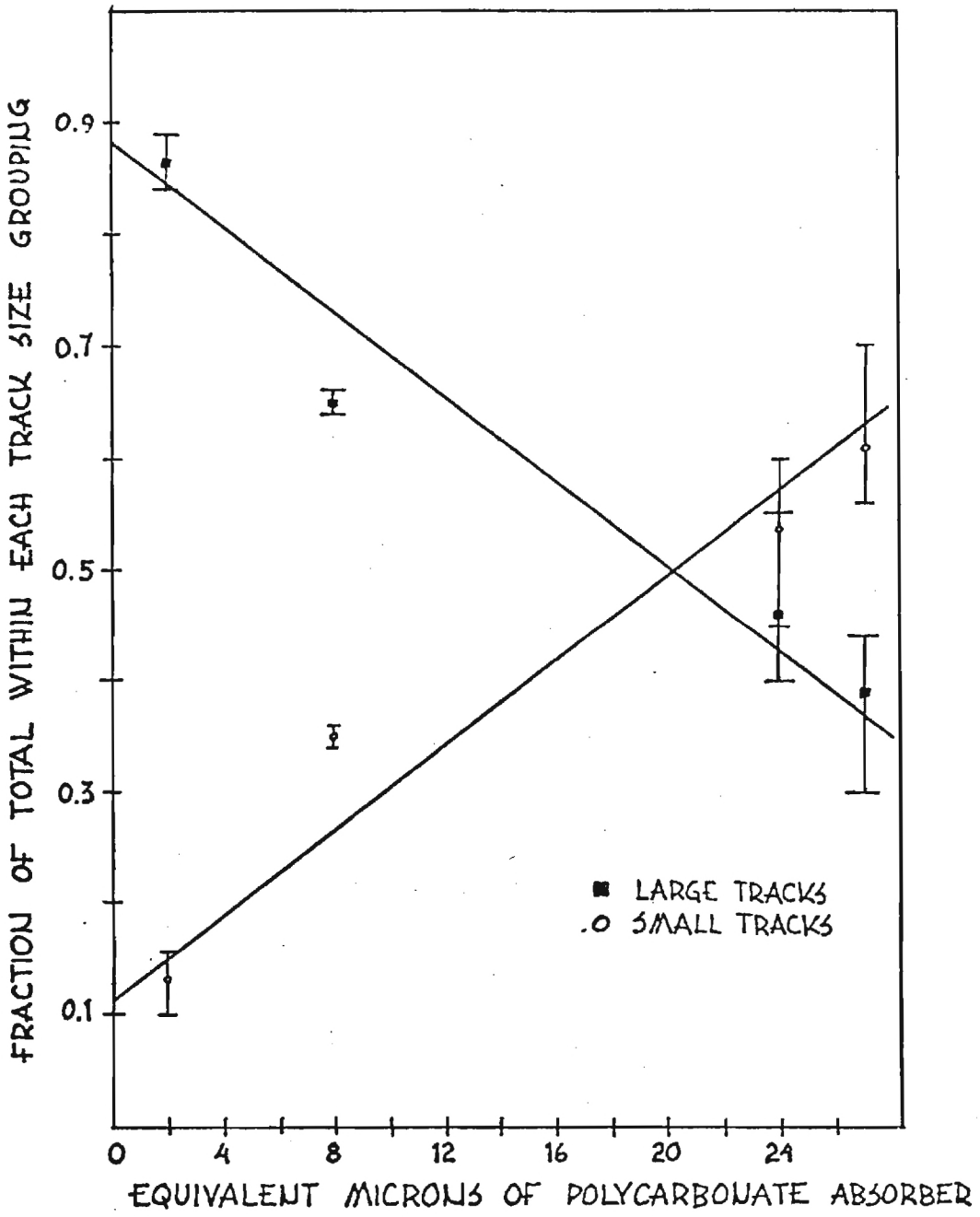


Figure 9. Change in the Fraction of the Total Number of Tracks on a Foil in Each Track Size Grouping. Upper Curve is the Large Tracks and Lower Curve, the Small Tracks.

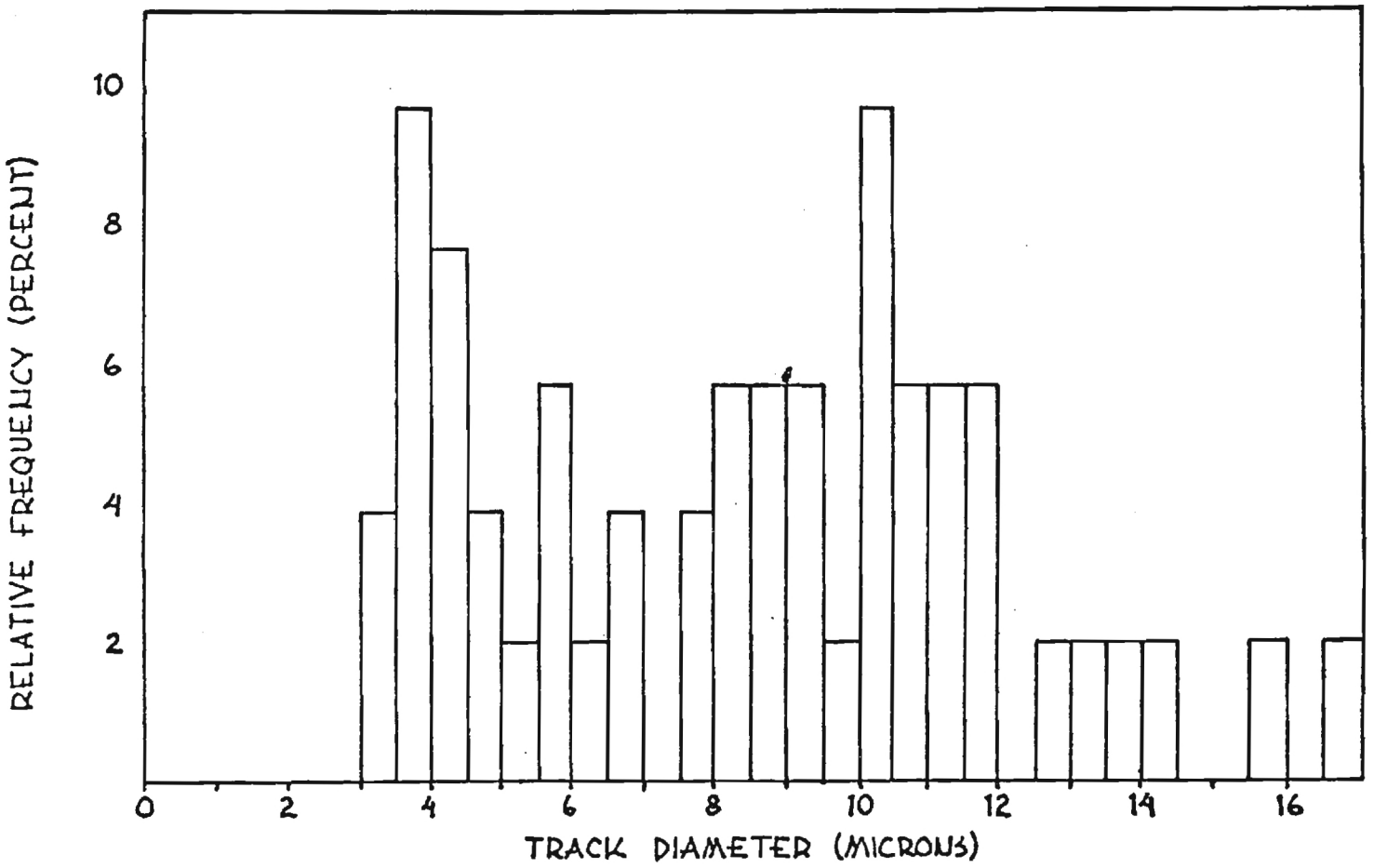


Figure 10. Relative Frequency of Track Diameters for a Foil Etched One Hour at 800 V, 2 KHZ, 24°C in 45% KOH.

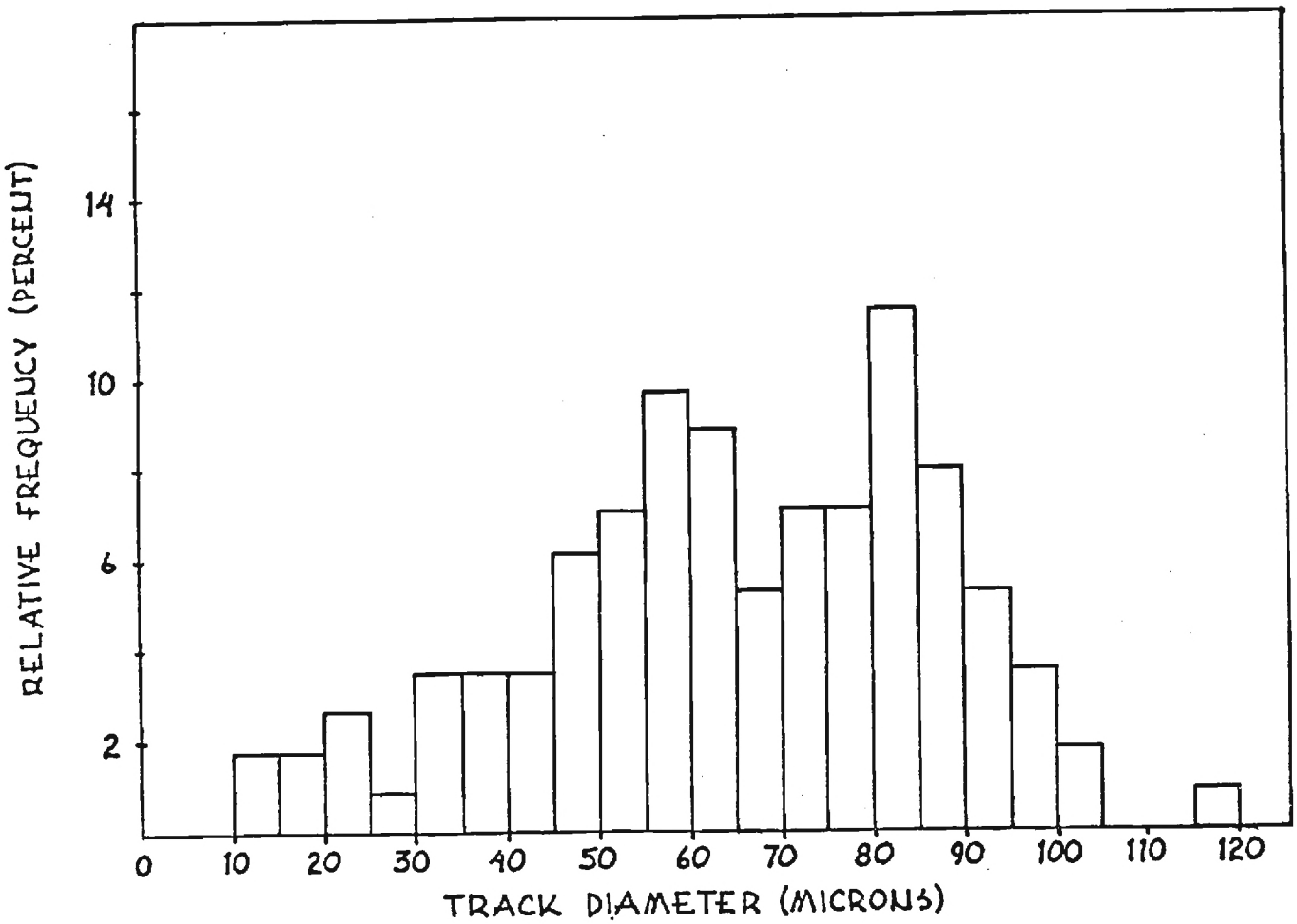


Figure 11. Relative Frequency of the Various Track Diameters for a Foil Using a 27 μm Absorber Between the Source and Foil. Ratio of Small Tracks to Large Tracks is 69:44. Etching Conditions were 800 V, 2 KHZ, 28%, 24°C, and 4 Hours Etching Time.

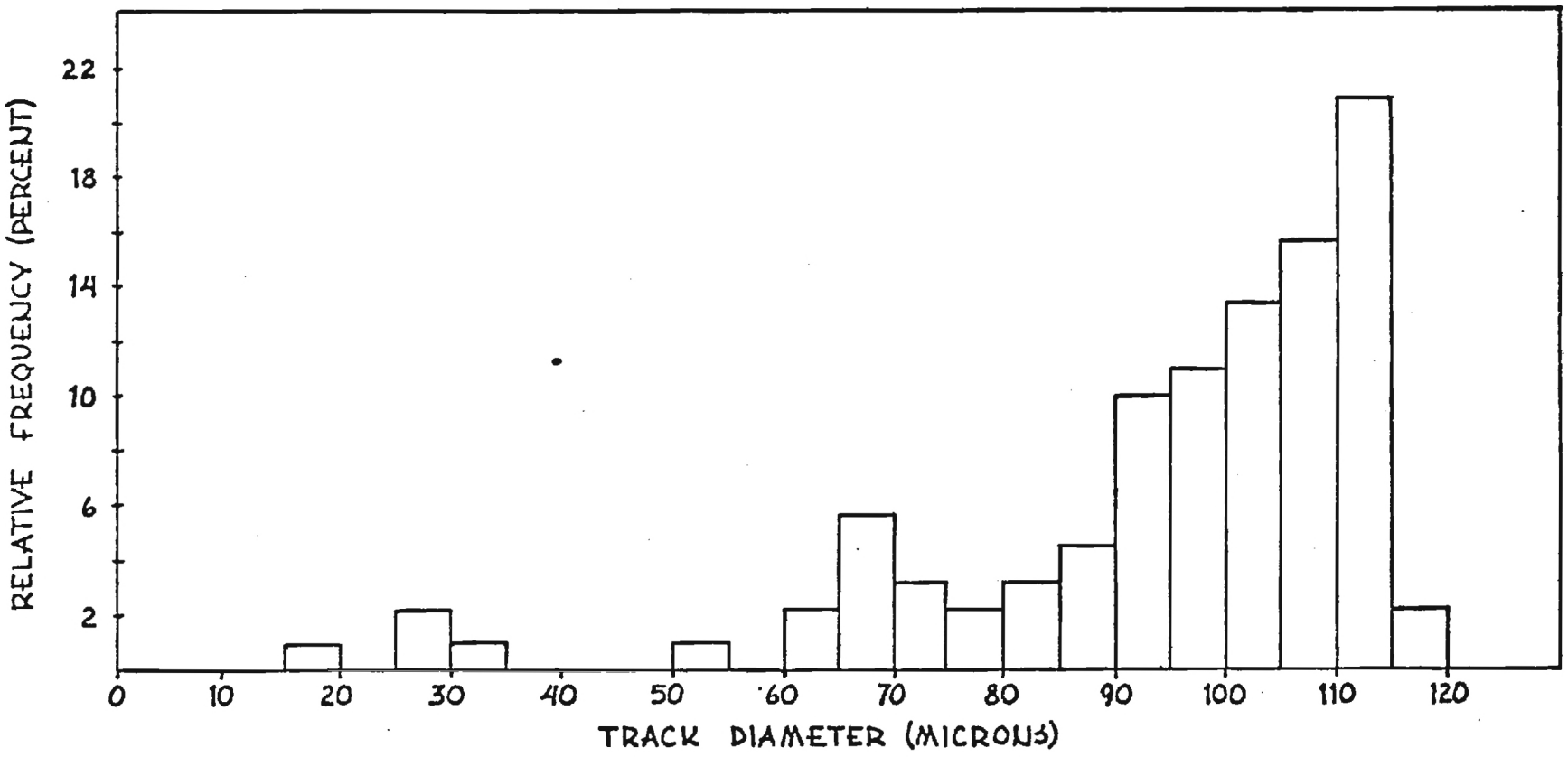


Figure 12. Relative Frequency of the Various Track Diameters for a Foil Using a 2 μm Absorber Between the Source and Foil. Ratio of Small Tracks to Large Tracks is 12:78. Etching Conditions were 800 V, 2 KHZ, 28% KOH, 24°C, and 4 Hours Etching Time.

thickness decreases, the track diameter shift from small to large tracks can be easily identified by viewing Fig. 11, then 12. The data contained on these foils were used to generate Fig. 9 in the following manner. According to Crawford,[56] " . . . physical processes forming particulate distributions tend to produce a log-normal distribution." Distributions such as the Poisson would not be expected to apply to the case here, namely single measurements of many different tracks, because distributions such as the normal and Poisson give the probability of a value n falling between n and n + dn. In other words, one is removing samples from one pool of data. It would be expected, however, that many diameter measurements of <u>one</u> track would describe a Poisson distribution. The log-normal distribution is used to describe particle distributions where one has many different particles of varying diameters, each of which is measured once and then particle diameter measurements are fitted to the log-normal distribution. This is essentially the situation we have with our track diameter measurements. From this point, the formulation of Crawford[56] was used. A range of diameters, d, was selected equal to 10 μm. The number of tracks falling into each range was determined as a fraction of the total number of tracks, $\Delta N/N$. Then each fraction was summed such that the last range of d gave a sum equal to 1.0. According to the method, if the values of each respective sum, $\Delta N(di)N$, are plotted against the high end of the appropriate diameter range, a straight line will result on probability-log paper if one log-normal distribution will describe the data. This provides a method of not only deciding how many tracks to assign to each track grouping, but

it also allows a method to further prove the existence of two size groupings of tracks. One of these curves appears on Fig. 13. Immediately apparent is the sharp break in the curve indicating the presence of two distributions. It is now quite simple to determine the fraction of the total number of tracks in the small group of tracks. The line drawn through the lower end of the curve, corresponding to the small tracks and extending until it crosses the largest track diameter encountered will be indicating the contribution of this distribution as a fraction of the total, 100%. This is the fraction of tracks which fall into the small track log-normal distribution. This procedure is not unlike the procedure used to separate the contribution of counts from a mixture of two nuclides of differing half lives, one short and the other long. The log-probability curves were plotted six times for each foil and the straight line representing the small track distribution plotted six times each. The average of these six values is plotted in Fig. 9 and the maximum and minimum values are indicated by the error bars (or error ranges). Therefore, when plotting Fig. 7, one curve represents the large track diameter as a function of etching time and the lower curve, the small track diameter as a function of etching time. The two mechanisms for track formation (i.e. the large and the small tracks) have not been identified by us, but it is possible (and we believe it is true that) the smaller tracks are created by alpha particles themselves and the larger tracks by recoil of carbon and oxygen nuclei produced in the polycarbonate. Of course, these latter interactions would not be of the elastic collision type found in fast neutron work because of the + 2

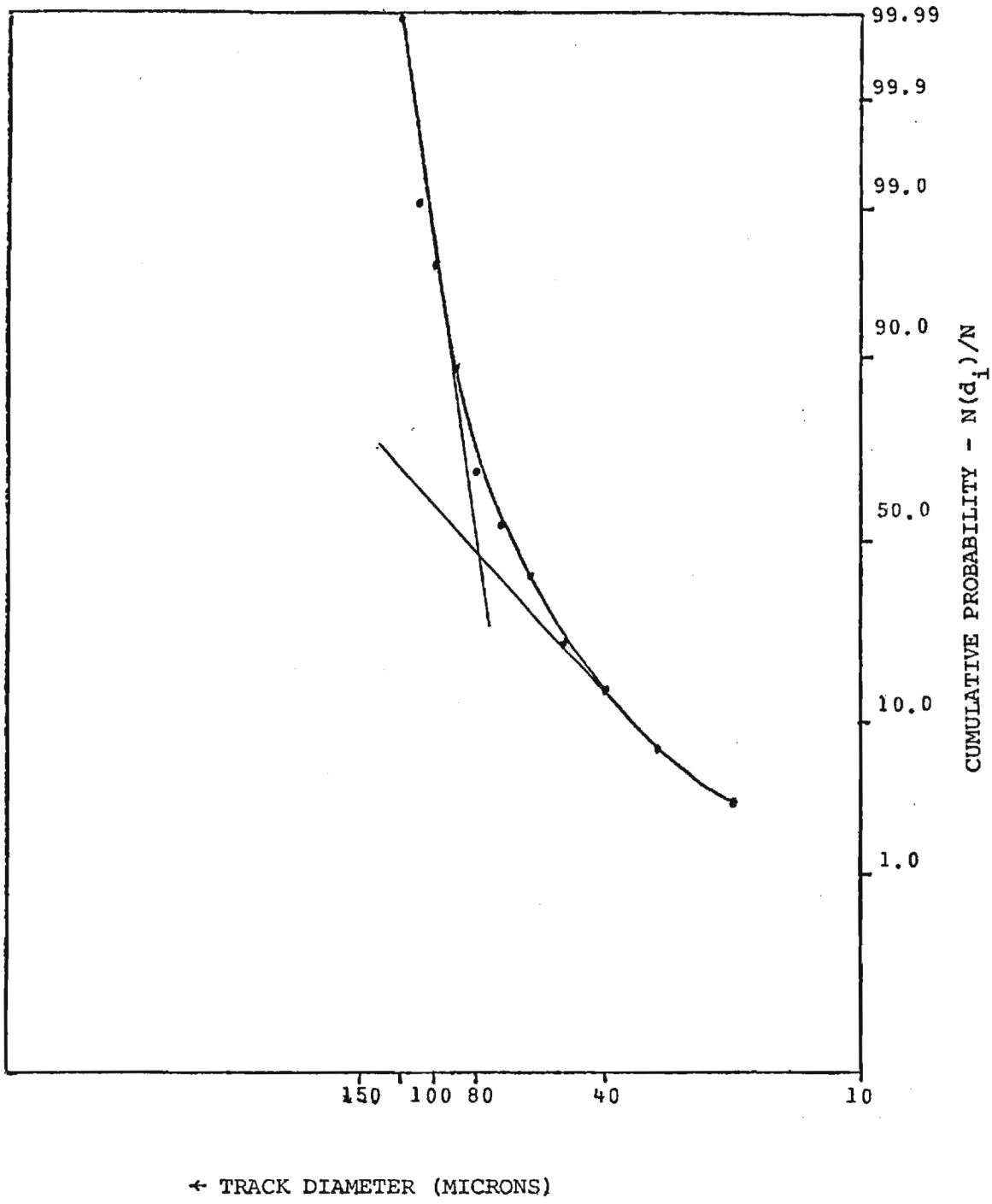


Figure 13. Plot of Cumulated Probability, $N(d_i)/N$, Versus Track Diameter (increasing to the left) for an Alpha Particle Irradiated Foil Electrochemically Etched Four Hours, at 800 V, 2KHz, 28% KOH and 24°C. Probability Refers to the Occurrence of a Particular Track Diameter.

charge of the alpha particle. Instead, we could envision a Coulombic repulsion event during which the target nucleus does not remain stationery, unlike classical Rutherford scattering, but is "pushed" out of its lattice site by this repulsive force. This event would be possible especially for high energy alpha particles and large angles of deflection since more energy would be imparted to the recoil nucleus than in the opposite situations. This type of interaction was introduced by Rutherford many years ago (Rutherford),[57] (Rutherford, et al).[58] Except for work using protons and helium nuclei, much of this early work was concerned with heavier nuclei such as argon, gold and copper in which this effect would be considerably reduced in importance due to the difference in mass between an alpha particle and, say, a gold nucleus. In polycarbonate and tissue the main target nuclei are carbon, oxygen, and protons. Two pieces of experimental evidence support this explanation we are suggesting for the appearance of large tracks. First, the track diameters for the group of large tracks is approximately the same as we have observed for recoil particle tracks after fast neutron irradiation (Su and Morgan).[59] Second, the number of large tracks <u>increased</u> and the smaller tracks <u>decreased</u> with decreasing absorber thickness, Fig. 9. The increase in large tracks would then be caused by the greater number of alpha particles possessing high energy. Thus, with less absorber, more alpha particles have sufficient energy to "push" the polymer nuclei out of their lattice sites. The decrease in smaller tracks would be caused by getting farther away from the Bragg peak where the highest LET is found for alpha particles and this may be the only region where

alpha particles possess a large enough stopping power -dE/Dx to cause a track of small diameter. With a larger absorber present, many more alpha particles could be expected to be found within the high LET portion of the Bragg curve and fewer possessing high energy or low -dE/dx. A decrease in the large diameter tracks, but an increase in the number of small diameter tracks as the Bragg peak is approached, could be anticipated with this explanation.

The data of Rutherford also support this explanation of the increase in numbers of large tracks with decreasing absorber thickness. His curve for helium nuclei as targets clearly show an increase in numbers of counts with increasing alpha particle energy, Fig. 14. Here the ratio $v_{o/v}$ is the velocity of the alpha particle velocity used to the velocity considered. The alpha sources used were "radium-active deposit" which was $^{218}Po$, $^{214}Pb$, and $^{214}Bi$ in equilibrium and "thorium-active deposit" which was $^{228}Th$. It is felt this effect could have ramifications in the field of internal dosimetry. To illustrate, we could examine the energy expected to be possessed by these light recoiling nuclei. A vector diagram for the interaction is shown in Fig. 15 where OA is the momentum vector for the incident alpha particle ($m\vec{v}_1$), OB for the scattered alpha particle ($m\vec{v}_2$), $\phi$, the angle of deflection, and BA is the momentum vector for recoiling nucleus ($M\vec{V}$). By the law of cosines

$$(MV)^2 = (mv_1)^2 + (mv_2)^2 - 2(mv_1)\ (mv_2)\ \cos\phi$$

and by conservation of energy

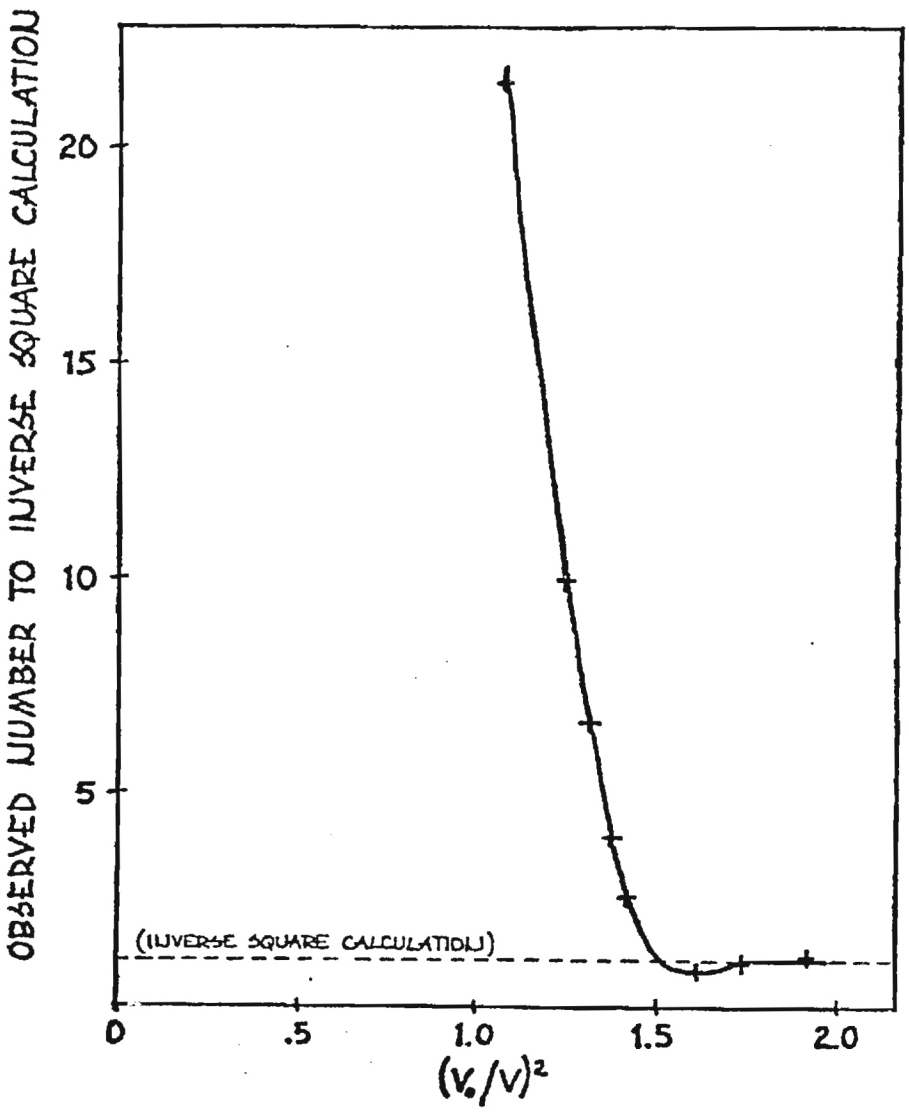


Figure 14. Graph Showing the Number of Counts Received on a ZnS Screen as a Function of Alpha Particle Velocity. Y-Axis is the Number Counts Observed Divided by that Expected from an Inverse Square Calculation and the X-Axis is the Velocity of the Alpha Particle Used (See Text) Divided by the Velocity Considered.

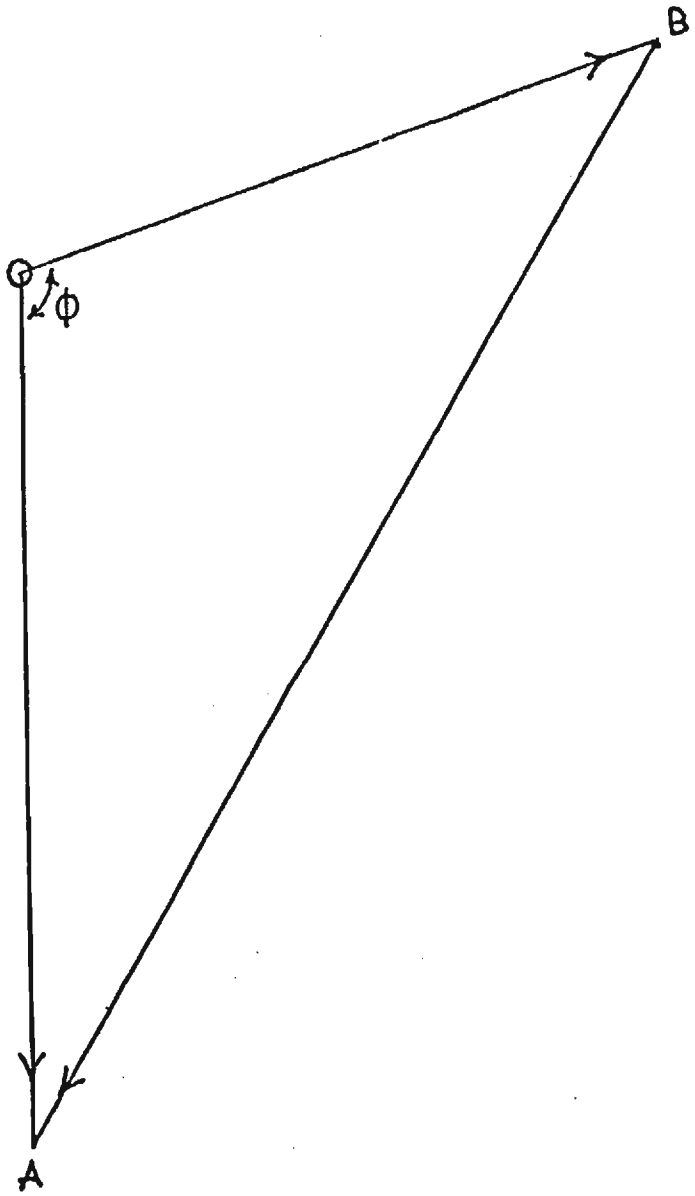


Figure 15. Vector Diagram Describing the Collision of an Alpha Particle and a Nucleus. The Momentum Vectors are $\vec{OA}$ for the Incoming Alpha Particle, $\vec{OB}$ for Scattered Alpha Particle, and $\vec{BA}$ for the Recoil Nucleus.

$$MV^2 = mv_1^2 - mv_2^2 \quad .$$

If we define $K = \frac{M}{m}$ and $v_2 = \rho v_1$, where $\rho < 1$ then from these two equations we quickly find

$$K - 1 = \rho^2(K + 1) - 2\rho \cos\phi$$

or

$$\rho = \frac{\cos\phi}{K + 1} + \frac{1}{K + 1} (K^2 - \sin^2\phi)^{\frac{1}{2}}$$

If we now assume an initial alpha particle energy of 5.1 MeV (approximately equal to a $^{239}Pu$ alpha particle), we can calculate the energy expected to be given to the recoil nucleus. These values appear on Table I for various angles, $\phi$. $E_2$ is the scattered alpha particle energy and $\Delta E$ is given to the recoiling nucleus. For gold at $90^o$ $\Delta E$ = 0.21 MeV and aluminum $\Delta E$ = 1.33 MeV so we can see how important the mass of the target nucleus is in determining the significance of this effect. For a head-on collision with a carbon nucleus almost 4 MeV is imparted to this nucleus. The implications in internal dosimetry are now becoming clearer. Instead of this 4 MeV being imparted to tissue by an alpha particle as we would assume in calculations of dose equivalent, this 4 MeV has been converted to a more efficient energy imparting means, e.g., a carbon nucleus. This could cause more severe damage to cells, especially in the close vicinity of the alpha emitters than we would expect when considereing only alpha particle energy deposition. Also, we have a direct mechanism now present to cause chromosome breakage. With this interaction atoms could be simply removed or knocked

Table I

| | K | $30^0$ | | | $60^0$ | | | $90^0$ | | | $150^0$ | | | $180^0$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\rho$ | $E_2$(MeV) | $\Delta E$(MeV) | $\rho$ | $E_2$ | $\Delta E$ | $\rho$ | $E_2$ | $\Delta E$ | $\rho$ | $E_2$ | $\Delta E$ | $\rho$ | $E_2$ | $\Delta E$ |
| Carbon | 3 | 0.956 | 4.66 | 0.44 | 0.843 | 3.63 | 1.48 | 0.707 | 2.55 | 2.55 | 0.523 | 1.40 | 3.71 | 0.500 | 1.28 | 3.83 |
| Oxygen | 4 | 0.967 | 4.77 | 0.33 | 0.881 | 3.96 | 1.44 | 0.775 | 3.06 | 2.04 | 0.621 | 1.97 | 3.13 | 0.600 | 1.84 | 3.26 |

The energy of the recoil nucleus, $\Delta E$, the scattered alpha particle energy, $E_2$, and the ratio of final to initial alpha particle velocity, $\rho$, are shown for various angles of deflection of the scattered alpha particle. $E_1 = 5.1$ MeV (initial alpha energy), $v_1 = 1.567 \times 10^9$ cm/sec and $m_\alpha = 6.647 \times 10^{-24}$ g.

out of a DNA chain causing irreparable damage to this chain and possibly other chains due to the higher LET of the removed carbon or oxygen nucleus. The interaction indicated here would be occurring in addition to those effects described by Katz.[60] This is a direct mechanism for permanent change in a cell nucleus that should be considered during discussion of carcinogeneity and other cellular effects.

One interesting side note is the possibility that the effect described above may never have been observed if the foils had not been composed of light nuclei as in tissue. This effect could actually be occuring in tissue since the main components of tissue are nuclei whose mass is not greatly different from the alpha particle. Therefore, large energy transfer can result from the alpha particle to the target nucleus as in the polycarbonate. When emulsions are used, this effect would not be expected to be observable due to the presence of heavy nuclei such as silver and halide nuclei. From Rutherford's work[57,58] we know these nuclei tend to remain stationery during interaction with the alpha particle since they are essentially infinitely heavy with respect to the alpha particle. This is classical Rutherford scattering. The observance of effects such as these is one argument in favor of using a tissue equivalent material whenever possible to detect the interactions of radiation with tissue. If this suggestion is not followed, important interactions may be overlooked simply because the dosimeter selected does not interact with the radiation in the same manner as tissue. We cannot pretend to know beforehand when tissue equivalence is not necessary. This discovery of the two track sizes and its possible application to radiation effects on tissue are further strong arguments for the importance

of this dosimetry system with regards to alpha particle dosimetry of internal emitters.

In our present work, samples of dog and human bones have been obtained, mounted, and are being exposed to the alpha emitters in the bones. The alpha particles in these bone samples cause tracks to be produced in polycarbonate foils pressed against the endosteal surface. The dog bones contain $^{239}Pu$ and were obtained from Dr. W. S. S. Jee at the University of Utah. The human bones contain low levels of various nuclides, some at the background level, others at a higher level as a result of accidents. These were obtained from Dr. B. D. Breitenstein, associated with the United States Transuranium Registry. We are most grateful to Doctors Jee and Breitenstein for this valuable contribution to this research.

## II. Neutron Dosimetry - Fast and Thermal

### A. Energy Dependence of Dosimeter Response

Registration of fast-neutron-induced recoil tracks by the electrochemical etching technique as applied to sensitive Lexan polycarbonate foils provides a simple and inexpensive means of fast neutron personnel dosimetry.

The sensitivity (tracks/neutron) of recoil particle registration is given in this study as a function of neutron energy. Neutrons of <4.3 MeV, 14 MeV, and 22 MeV were produced by the reactions $^{7}Li(p,n)^{7}Be$, $^{3}T(d,n)^{4}He$, and $^{9}Be(d,n)^{10}B$, respectively. Results are compared with other studies using other neutron sources and the conventional etching method.

The foils were irradiated in air to fast neutrons of different energy spectra from the Van de Graaff accelerator at the Institute of Nuclear Energy Research of Taiwan, 14 MeV neutrons from the Cockcroft-Walton accelerator at the National Taiwan University, and the Texas A & M University Cyclotron by the $^{9}Be(d,n)^{10}B$ reaction. The neutron dose estimates given in these studies were based upon dosimetry reports provided by the above facilities.

The irradiated foils were etched by an electrochemical etching system (Soharbi),[9] (Su, et al).[7] Unlike conventional etching methods which can be carried out by immersing the foils in a chemical solution of a certain concentration and temperature, electrochemical etching requires special etching equipment. This etching system consists of an etching chamber and a high voltage power supply to provide the

necessary voltage and frequency across the chamber. The equipment used in this study consists of two cylindrical Lucite chambers, each 5 cm in length and 13 cm in diameter, and has the capacity to etch seven foils simultaneously. The irradiated foils to be etched are placed between the containers. They are held in place at each window connecting the two chambers (the number of foils is equal to the number of windows) by two packings in such a way as to isolate the two chambers electrically. The chambers are filled with 45% KOH etchant solution at room temperature. A high voltage is applied across the chambers by means of two stainless steel electrodes that dip into the eletrolite of each chamber. The high voltage is generated by an audiofrequency oscillator; the output of which is amplified by a push-pull amplifier to supply the necessary voltage and frequency (e.g., 800 V, 2 KHz). After the proper etching time (e.g., 4 hours), the foils are removed from the chamber, washed and dried for track counting. The track densities reported here were obtained by a microfiche reader at 53X magnification, and the track densities are the sum of the track densities appearing on both sides of a foil. A Poisson distribution assumption is employed for the counting error estimation (Su).[7]

Neutron Sources: Table II summarizes some characteristics of fast neutron sources used in this study. Monoenergetic neutron sources below 4.335 MeV were produced with a 7 MV Van de Graaff accelerator using d.c. beam via the $^{7}Li(p,n)^{7}Be$ reaction (Q value = -1.644 MeV). Neutrons emitted at different angles with respect to the Van de Graaff beam were used for the irradiations, Fig. 16. The lithium targets were prepared by vacuum evaporation of metallic lithium on tantalum backing. The

TABLE II. FAST NEUTRON SOURCES USED IN THIS STUDY

| | Source | Facility | Neutron Energy (MeV) | Fluence ($^n/cm^2$) | Distance Between Target & Sample (cm) |
|---|---|---|---|---|---|
| 1. | Fission Neutrons | Ga. Tech Atlanta, Ga. | 1.2 | $10^7$-$10^9$ | 10 |
| 2. | $^7Li$ (p,n) $^7Be$ | INER Taiwan | 0.7-4.3 | $10^6$-$10^9$ | 20 |
| 3. | $^3T$ (d,n) $^4He$ | National Taiwan U. Taiwan | 14.1-15.0 | $4.5x10^8$ | 15 |
| 4. | $^9Be$ (d,n) $^{10}B$ | Texas A & M U. College Station, Texas | 22 | $10^6$-$10^{10}$ | 20 |

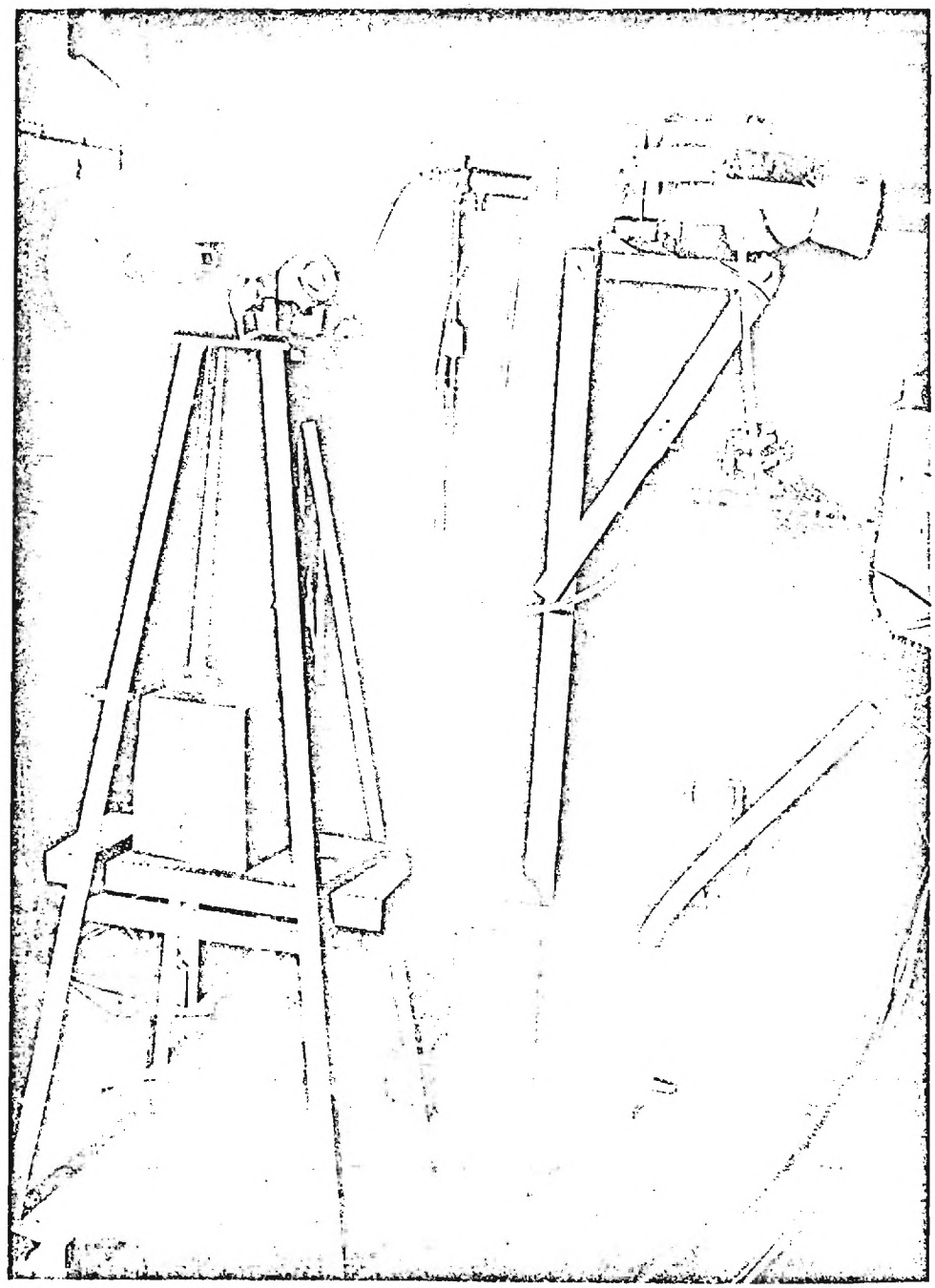

Fig.16 Irradiation Facilities for $^{7}Li\ (p,n)\ ^{7}Be$

thickness of the metallic lithium target used was 500 μg/cm$^2$. Four polycarbonate foils of 10 x 24 cm each were supported around the target (from - 135° to 135°) by a wooden shelf. The distance between the target and the sample was 20 cm. The target was at the level of the samples during the irradiation, 1.4 meters above the floor. For these exposures, the currents of protons were varied from 0.5 μA up to 2.0 μA and the energies were varied from 3 MeV up to 6 MeV. Figure 17 shows the neutron energies as a function of laboratory angles at different bombarding proton energies (Marion and Fowler).[61] A proton recoil telescope was used for the absolute determination of monoenergetic neutron flux (Wu and Chou).[62] The telescope consists principally of a solid radiator and n-type silicon surface barrier detector. The pulse from a charge-sensitive preamplifier located to the silicon detector is shaped and amplified by a linear amplifier and then analyzed and recorded in a multichannel analyzer.

Sources of error are from (1) total n-p cross section; (2) thickness of radiator; (3) telescope geometry; (4) efficiency calculation; (5) statistical uncertainty of proton counts; and (6) uncertainty of background. The total estimated error is about 3%.

Neutrons emitted at different angles with respect to the deuteron beam were produced at the 250 KV Cockcroft-Walton accelerator in National Taiwan University by the D-T reaction, Fig. 18. The absolute measurement of neutron yield and angular distribution were carried out by counting α-particles with a thin (0.1 mm) ZnS crystal, which was placed at the position 1 m distance from zirconium-tritium target.

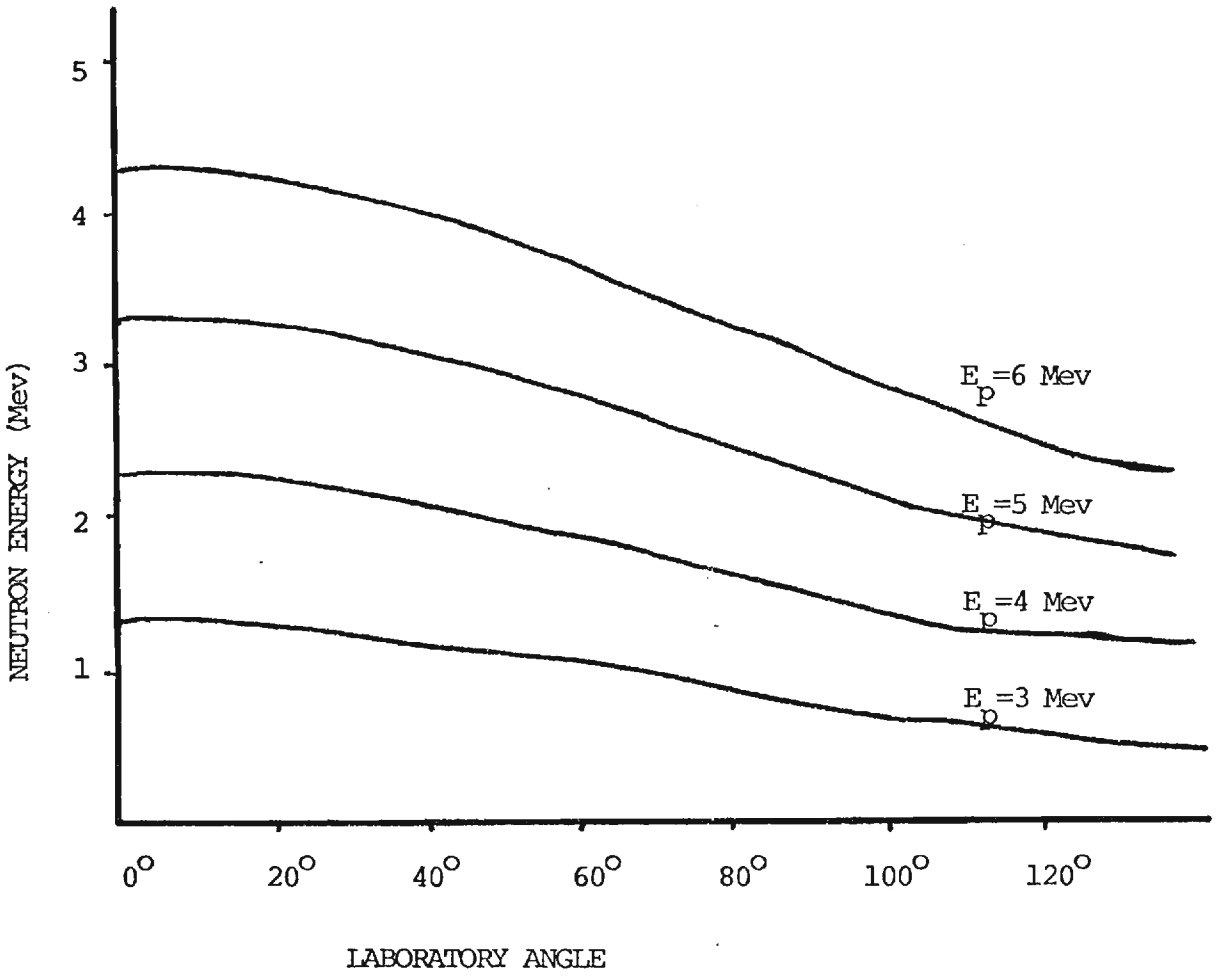


Fig.17. Neutron Energies from the $^{7}Li(p,n)^{7}Be$ Reactions As A Function of Bombarding Energy and Laboratory Angle

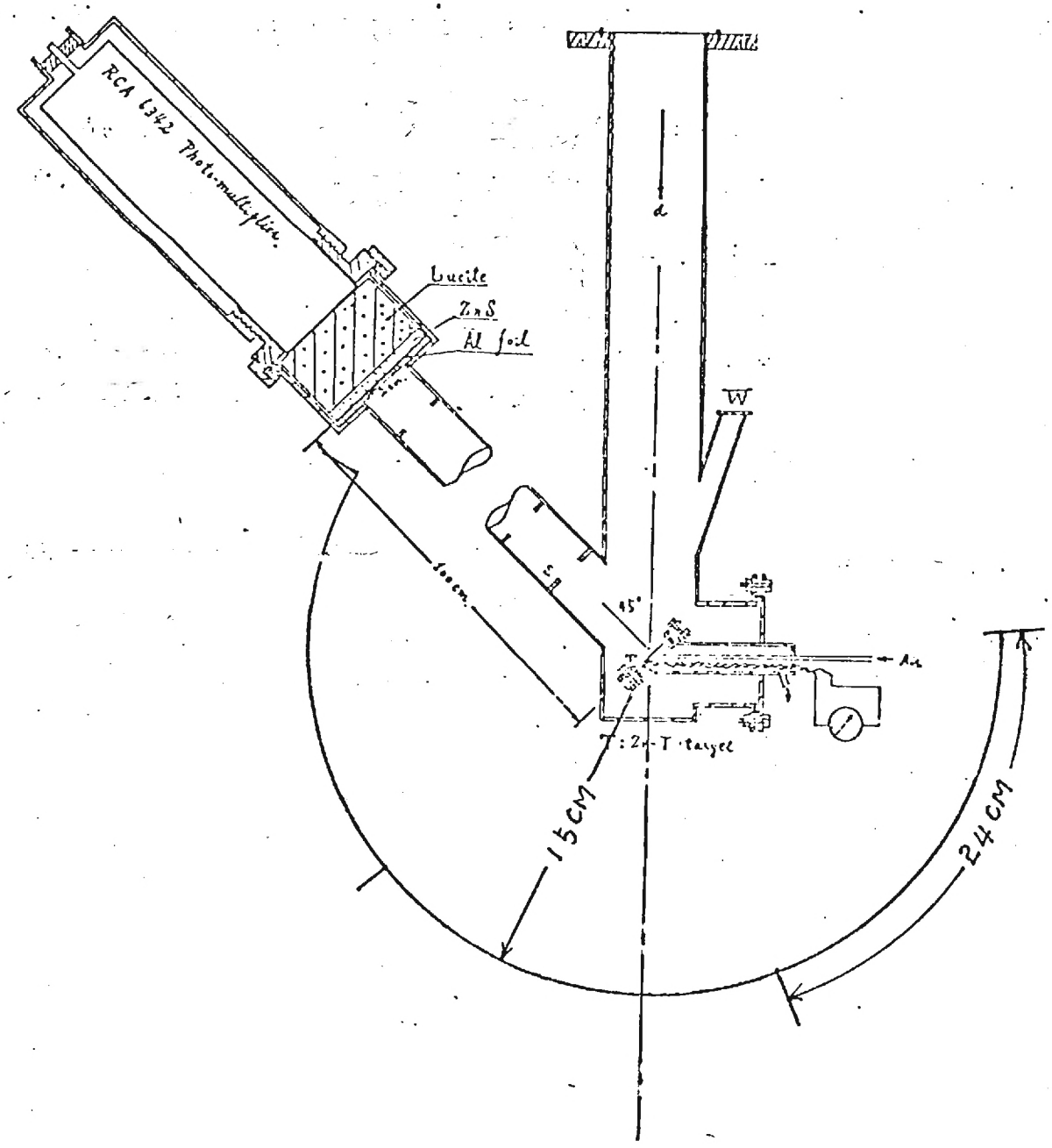


Fig. 18. Irradiation Facilities for T (d,n) $^4$He

The very high Q value of T (d,n) reaction, 17.586 MeV, makes possible the production of high neutron energy with relatively low input energy. The neutron energy is relatively insensitive to the angle of emission for the region of low deuteron bombarding energy. At a deuteron energy of 200 KeV, the neutron energies varied around 14.15 MeV at 90° by only about ±7 percent. The total neutron fluences striking our polycarbonate foils varied from $4.78 \times 10^8$ to $4.25 \times 10^8$ $n/cm^2$ at different angles.

Figure 19 shows fast-neutron-induced recoil particle track diameter distributions in 250 μm Lexan polycarbonate foils for three different neutron sources: 2.26 MeV, 4.25 MeV, and 14 MeV. Each distribution was obtained from 200 randomly scanned tracks. All track diameters were measured under a light microscope with micrometer. Obviously, there are distinct difference in the distributions and the distributions are skewed more to the right as the neutron energy increases. The mean track diameters for the three neutron sources are 34.7, 48.1, and 55.1 μm, respectively, for 2.26 MeV, 4.25 MeV, and 14 MeV. Thus, the mean track diameters and the track diameter distributions can be used as a measurement of neutron energy.

In Fig. 20, sensitivity (tracks/n) of recoil particle track registration is given as a function of neutron energy by three different investigations, reported by Becker,[63] Sohrabi,[9] and this study. The first neutron energy dependence studied by Becker was carried out using the conventional etching method. The sensitivities obtained by electrochemical etching of Sohrabi and this study are lower than the values obtained by conventional etching. The reasons could be (1) The recoil tracks registered on the surface layers are electrochemically

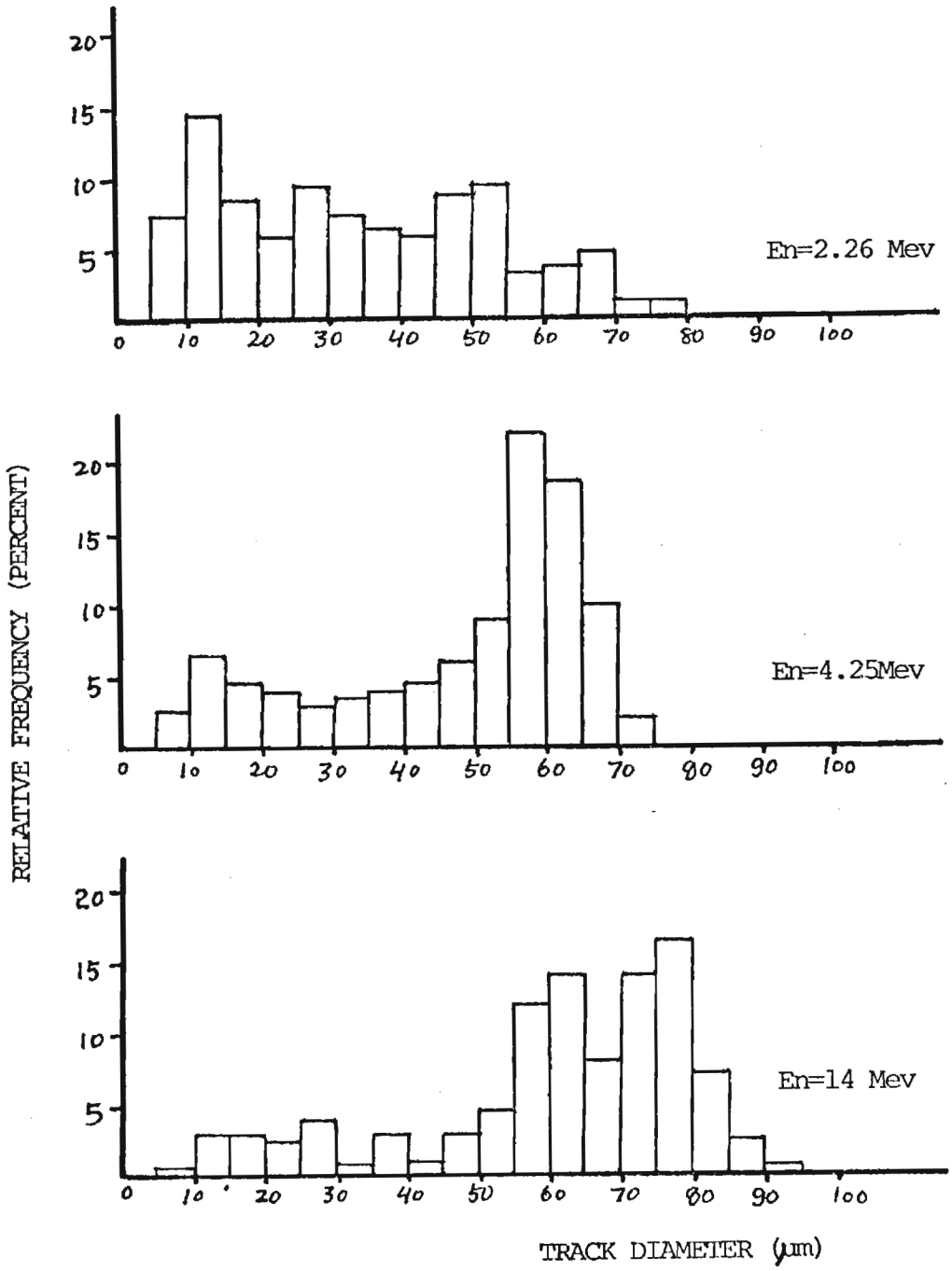


Fig.19 Track Diameter Distribution in 250 μm Polycarbonate Foils

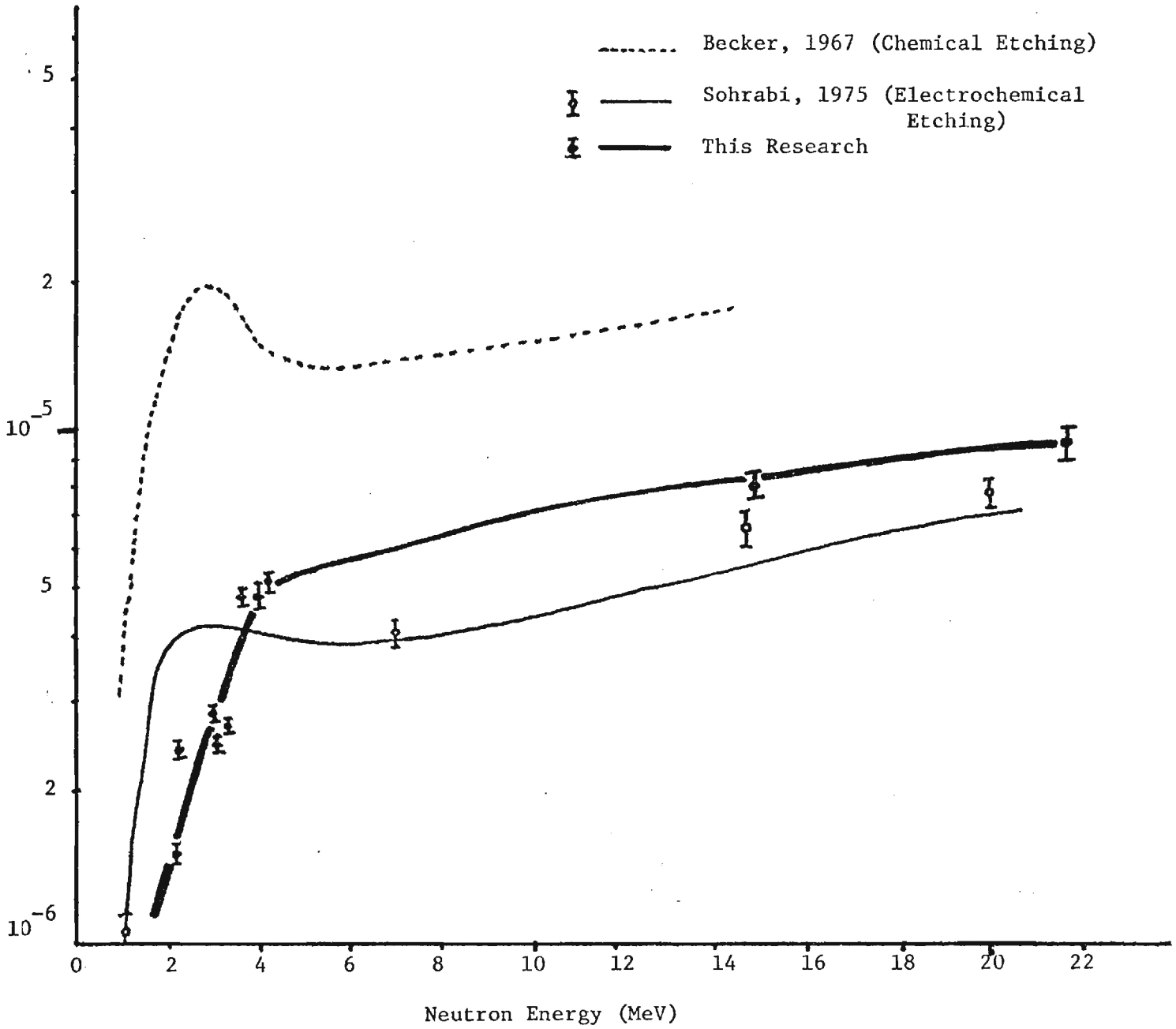


Fig. 20 Neutron Sensitivity (tracks/n) as a Function of Neutron Energy.

etched under the non-equilibrium conditions, (2) Conventional etching is carried out at a higher temperature than electrochemical etching.

Both theoretical and experimental results show a neutron threshold energy of about 1.4 MeV for fast-neutron-induced recoil particle track registration in polycarbonate. Polycarbonate foils are able to register fast neutrons by recording carbon and oxygen recoil atoms from neutron elastic collisions as well as alpha particles from $C(n,\alpha)$ and $O(n,\alpha)$ reactions. The $(n,\alpha)$ reactions in C and O take place for neutron energy values exceeding several MeV (ICRU).[64] The neutron elastic collisions with atoms of polymer take place for neutrons of all energies. Katz and Kobetich[65] calculated for several ions the ionization energy dosage at the critical distance from the ion's path depending on the particle energy. Based on the curves drawn for Lexan polycarbonate with the marked limits of the critical value of ionization energy dosage, one can find that carbon and oxygen recoils could form etchable tracks if their energy exceeds the limits of 2.6 to 2.9 x $10^{-2}$ MeV/amu, i.e., 0.32 to 0.35 MeV for carbon, and 2.3 to 2.5 x $10^{-2}$ MeV/amu, i.e., 0.37 to 0.40 MeV for oxygen. Maximum energy transfer in "head on" collision is equal to 0.284 for neutron-carbon collision and 0.222 for neutron-oxygen collision. Thus, the maximum neutron energy needed for carbon recoil registration in polycarbonate will be in the limits of 1.13 to 1.23 MeV, for oxygen recoil, 1.65 to 1.80 MeV.

## B. Thermal Neutron Dosimetry

The fact that the polycarbonate foil can detect alpha particles (Stillwagon and Morgan),[4] but is relatively insensitive to beta particles, gamma rays and thermal neutrons (Sohrabi),[9] gives it the

potential for enhanced use in certain dosimetric and autoradiographic applications.

Natural lithium is composed of 7.42% $^{6}Li$ and 92.58% $^{7}Li$. The latter has a negligible capture cross section for thermal neutrons (0.037b) compared with the value of 940.25 barns for $^{6}Li$ (Stewart).[66] The $^{7}Li$ nucleus produced by capture of a neutron by $^{6}Li$ is unstable and disintegrate at once by alpha emission with a Q-value of 4.788 ±0.023 MeV (Kaplan).[67]

The system described here uses $^{6}Li$ F as a radiator combined with Lexan polycarbonate foils for thermal neutron detection. The main advantage of this combination is that the $^{6}Li$ F thermal-neutron and fast-neutron response described above are both permanently recorded on one polycarbonate foil, since the $^{6}Li$ F in contact with the foil acts as a radiator producing holes in the foil from the $^{6}Li(n,\alpha)T$ reaction. Some of the many advantages of this method over the conventional nuclear emulsions are that polycarbonate foils are insensitive to light, require no darkroom processing, are relatively insensitive to normal environmental conditions (Sohrabi),[9] and there is essentially no fading of the tracks.

Lithium fluoride was used as a radiator in this study. A tablet form was preferred over a layer of powder because tablets would be more reproducible and easier to handle during experiments. The thickness of the radiator tablet should be greater than the range in lithium fluoride of tritons and alpha particles emitted from the $^{6}Li(n,\alpha)T$ reaction in order to maximize the number of particles that could reach the foil and produce tracks. The 4.78 MeV energy produced in this reaction is divided as kinetic energy between the tritons and the alpha

particles in approximately the inverse ratio of their masses. The range of the 2.7 MeV tritons in lithium fluoride was calculated to be approximately 12 μ, and the range of the 2.0 MeV alpha would be 6.6 μ. Although tablets are difficult to be pressed so thin, it was desired to make them as thin as possible to minimize the self-shielding effect of the $^{6}Li$.

0.3 g of KBr was used as a binder and added to 1.0 g of Li F. Each of the mixtures was ground with a marble mortar to obtain a fine and uniform mixture before the process of pressing the tablets. Different masses of the mixture were pressed into a 1.2 cm diamter tablet. Table III describes some characteristics of radiators made by natural Li F and enriched $^{6}Li$ F (99.3% enrichment obtained from Harshaw Chemical Co.). The 0.84 mm tablet was rather fragile but could be used as a radiator if handled carefully. The other thicknesses were even more fragile.

Gold foils were used for determining the thermal neutron flux at the position of irradiation. This gold foil disc, approximately 1 cm in diameter and 0.01 in. in thickness, was activated by irradiating it at the same position of the polycarbonate foil that was 10 cm away from the $^{252}Cf$ source using 5 cm of paraffin as a moderator.

The activity for such gold foil was calculated by a gamma spectroscopy counting system described in Appendix A. The thermal neutron flux density ($n/cm^2 . s$) at the position of irradiation was calculated by the following equation:

$$\phi = \frac{\dot{N}}{m} \times \frac{A}{(60) \times (6.02 \times 10^{23}) \times \sigma \times E \times f \ (1-e^{-\lambda t_i})}$$

Table III. Natural and Enriched LiF Radiators

| Radiator | Mass of Mixture (g) | $^{6}Li$ Abundance (%) | Mass of $^{6}Li$ (g) | Thickness of Tablet (mm) |
|---|---|---|---|---|
| 1 | 0.13 | 7.42 | 0.00742 | 0.44 |
| 2 | 0.15 | 7.42 | 0.00856 | 0.50 |
| 3 | 0.20 | 7.42 | 0.0114 | 0.07 |
| 4 | 0.25 | 7.42 | 0.0143 | 0.84 |
| 5 | 0.1 | 99.3 | 0.0764 | 0.34 |
| 6 | 0.15 | 99.3 | 0.115 | 0.50 |
| 7 | 0.20 | 99.3 | 0.153 | 0.67 |
| 8 | 0.25 | 99.3 | 0.191 | 0.84 |

where

$\phi$ = Thermal neutron flux density, $n/cm^2 \cdot s$

$\dot{N}$ = Net counting rate of gold foil, cpm

m = Mass of gold foil, g

A = Atomic weight of gold, 196.967 g/mole

60 = Conversion factor, s/min

$\sigma$ = Thermal neutron capture cross section of gold, $98.8 \times 10^{-24}$ $cm^2$

E = Counting efficiency, $c/\gamma$

f = Fraction of $^{198}Au$ decay at 412 KeV gamma peak, 0.95 $\gamma$/dis

ti = Irradiation time, min

The calculated thermal neutron flux density at a distance of 10 cm from the center of the 4 µg $^{252}Cf$ source using 5 cm of paraffin moderator was $1.05 \times 10^3 \pm 1.07 \times 10^2$ $n/cm^2$-s.

Preliminary Study: A preliminary study was performed to conform that the lithium fluoride radiator and 250 µm polycarbonate foil combination would exhibit an appropriate track density response under thermal neutron irradiation due to the $^6Li(n,\alpha)T$ reactions. The radiator was put in intimate contact with the foil and then the two were taped together. Three foils, each with radiators described in Table III, were placed behind the 5 cm paraffin moderator and irradiated with a $^{252}Cf$ source for 1 day which corresponded to the thermal neutron fluence of approximately $(9.07 \pm 0.925) \times 10^7$ $n/cm^2$. A control foil without a radiator was used during each irradiation to monitor the fast neutron response. The polycarbonate foils were electrochemically etched in a 45 percent KOH solution at 20°C applying 800 V at two kHz for four hours. Clusters of tiny tracks were found on the foil side

facing the Li F radiators. The larger tracks were found on both sides of the foils, while no small tracks were found on the foil side without radiators. The track densities and sensitivities are presented in Table IV. Poisson distribution was applied in the foils without radiators for error analysis (Su, et al.).[7] Thermal neutron track distributions were rather inhomogeneous so variance analysis was applied for the foils with radiators. The conversion factor for thermal neutron is 205 $n/cm^2.s$ for 1 mrem/h, so the minimum detection limit of thermal neutron dose equivalent from this preliminary study is 1 mrem.

Discussion: Figure 21 shows the track diameter distribution on polycarbonate foils with and without radiator, respectively. Track diameters produced by direct interaction of fast neutrons with polycarbonate foils (i.e. fast-neutron-induced recoil particle tracks) as previously stated are around 70 μm (Su and Morgan).[59] Alpha particles and tritons from $^6Li(n,\alpha)T$ reactions have lower LET than carbon and oxygen recoil particles. Therefore, their track diameters should be lower than tracks caused by fast neutrons, i.e. most tracks below 21 μm.

Other Studies in Progress: Some kind of holder for the radiator and foil must be designed in order to improve the homogeneous distribution of the thermal neutron tracks.

Detailed study must be performed to measure the track density response of polycarbonate foils and lithium fluoride radiators as a function of the $^6Li$ abundance in the radiators and of the thermal neutron fluence. It was obvious that the ratio between the track density in the foil under the radiator was not always related to their relative $^6Li$ F content. It seems to be influenced by the difference in the self-shielding effect which exists for the radiator tablet at low neutron energies.

Table IV. Track Counting Data

| Foil | $^{6}$Li mass (g) | Tablet Thickness (mm) | Track Density (track/cm$^2$) | | Sensitivity (tracks/nth) |
|---|---|---|---|---|---|
| | | | No Radiator | With Radiator | |
| 1 | 0.00742 | 0.44 | 72.6±8.5 | 407±97.5 | (3.69±1.14) x $10^{-6}$ |
| 5 | 0.0764 | 0.34 | 80.6±9.0 | 2311±725 | (17.5±8.1) x $10^{-6}$ |
| 8 | 0.191 | 0.84 | 74.1±8.6 | 3496±790 | (37.7±9.44) x $10^{-6}$ |

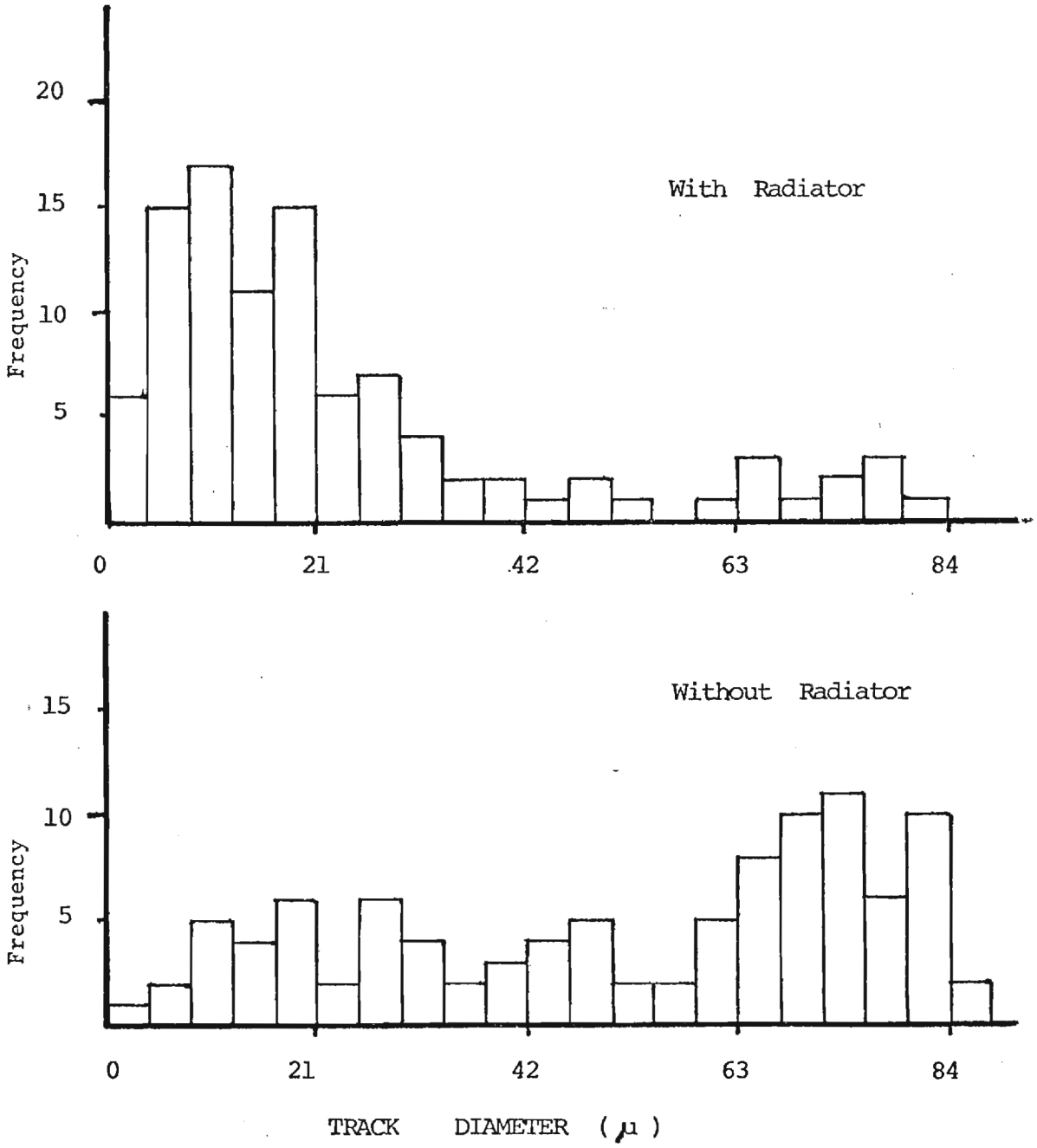


Figure 21. Track Diameter Distribution

## Appendix A

### Gamma Spectroscopy Counting System for Gold-198

Gold foils were used for determining the thermal neutron flux density. A gold-198 standard source was not available; therefore, the counting efficiency was based on other gamma-emitting standards. The standard reference sources prepared by the NBS consist of cobalt-57, cobalt-60, strontium-85, yttrium-88, cadmium-109 - silver-109 m, tin-113 - indium-113 m, cesium-137 - barium-137 m, cerium-139, and mercury-203, deposited as the chloride and sulfides, on polyester tape approximately 0.006 cm thick and cover by another layer of the same tape. The gamma-ray-emission rates at 1200 EST September 1, 1977 are shown in Table V.

A gamma spectroscopy counting system consisting of the following components was used to count the gold foils; (1) a co-axial Ge(Li) detector, model number B101-0324E by Ortec, (2) a high voltage power supply, model number 3005 by Canberra, (3) a preamplifier, model number 119 by Ortec, (4) linear amplifier model number 1413 by Canberra, and (5) multichannel pulse height analyzer with 1024 channels, model number 8100 by Canberra.

The energy calibration curve is shown in Fig. 22. This curve shows that the 412 KeV peak from $^{198}Au$ should occur in the neighborhood of channel 290. The counting efficiencies, as corrected for decay, are presented in Table VI and are plotted as a function of gamma-ray energy in Fig. 23.

The following equations were used to compute the counts (N) at the total absorption peak and the experimental standard error ($\sigma$) (Covell).[68]

Table VI Counting Efficiencies of the Standard Sources

| Source | Energy (MeV) | Channel Number | Counting Efficiency (c/γ) |
|---|---|---|---|
| $^{109}Cd$ | 0.088 | 62 | 0.0152±0.00065 |
| $^{57}Co$ | 0.122 | 86 | 0.0261±0.00066 |
| $^{139}Ce$ | 0.166 | 117 | 0.0259±0.0019 |
| $^{113}Sn$ | 0.392 | 277 | 0.00748±0.00048 |
| $^{85}Sr$ | 0.514 | 364 | 0.00604±0.00080 |
| $^{137}Cs$ | 0.662 | 468 | 0.00362±0.00014 |
| $^{88}Y$ | 0.898 | 636 | 0.00253±0.000082 |
| $^{60}Co$ | 1.173 | 831 | 0.00183±0.000038 |
| $^{60}Co$ | 1.332 | 943 | 0.00157±0.000037 |

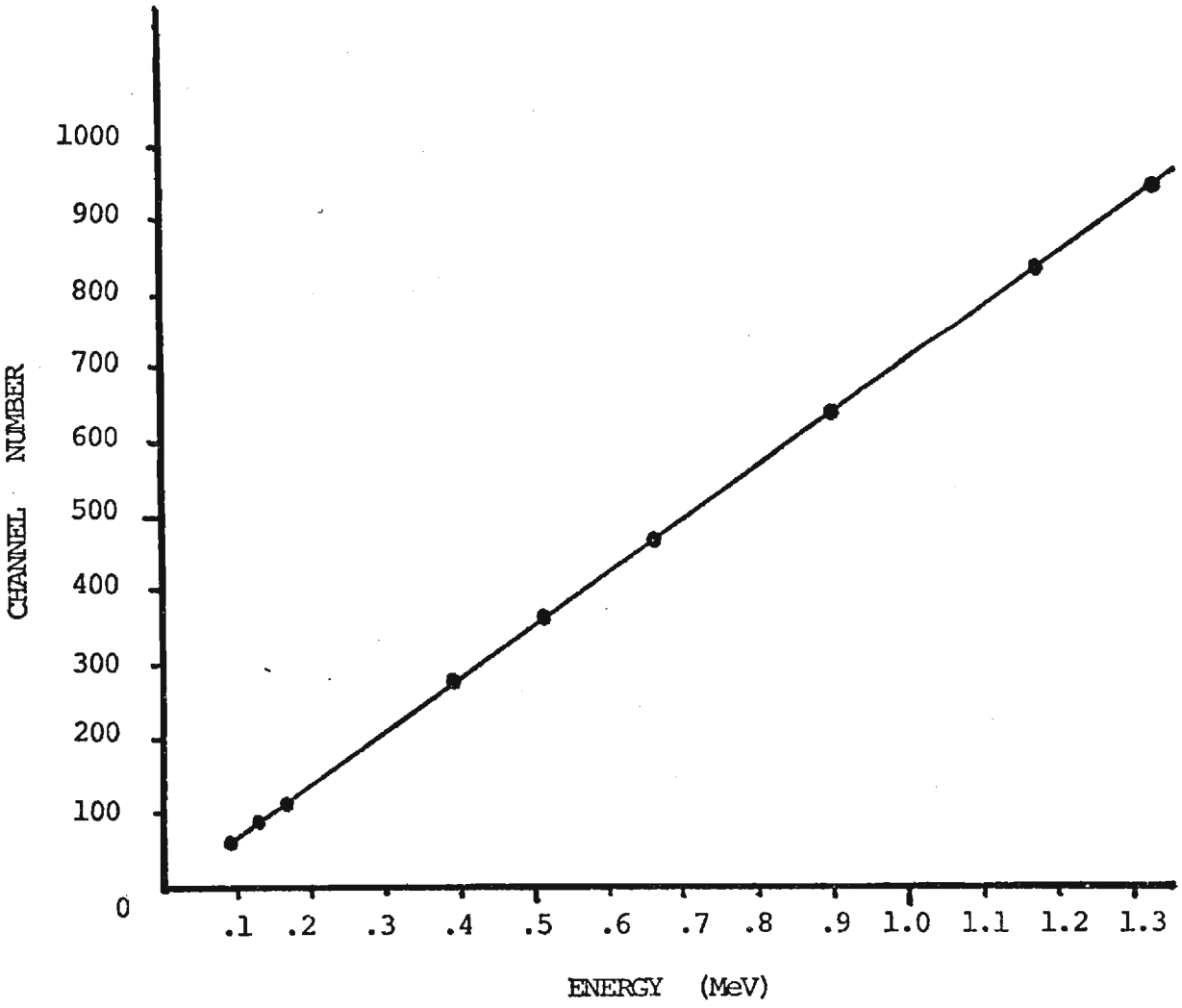


Figure 22. Energy Calibration Curve

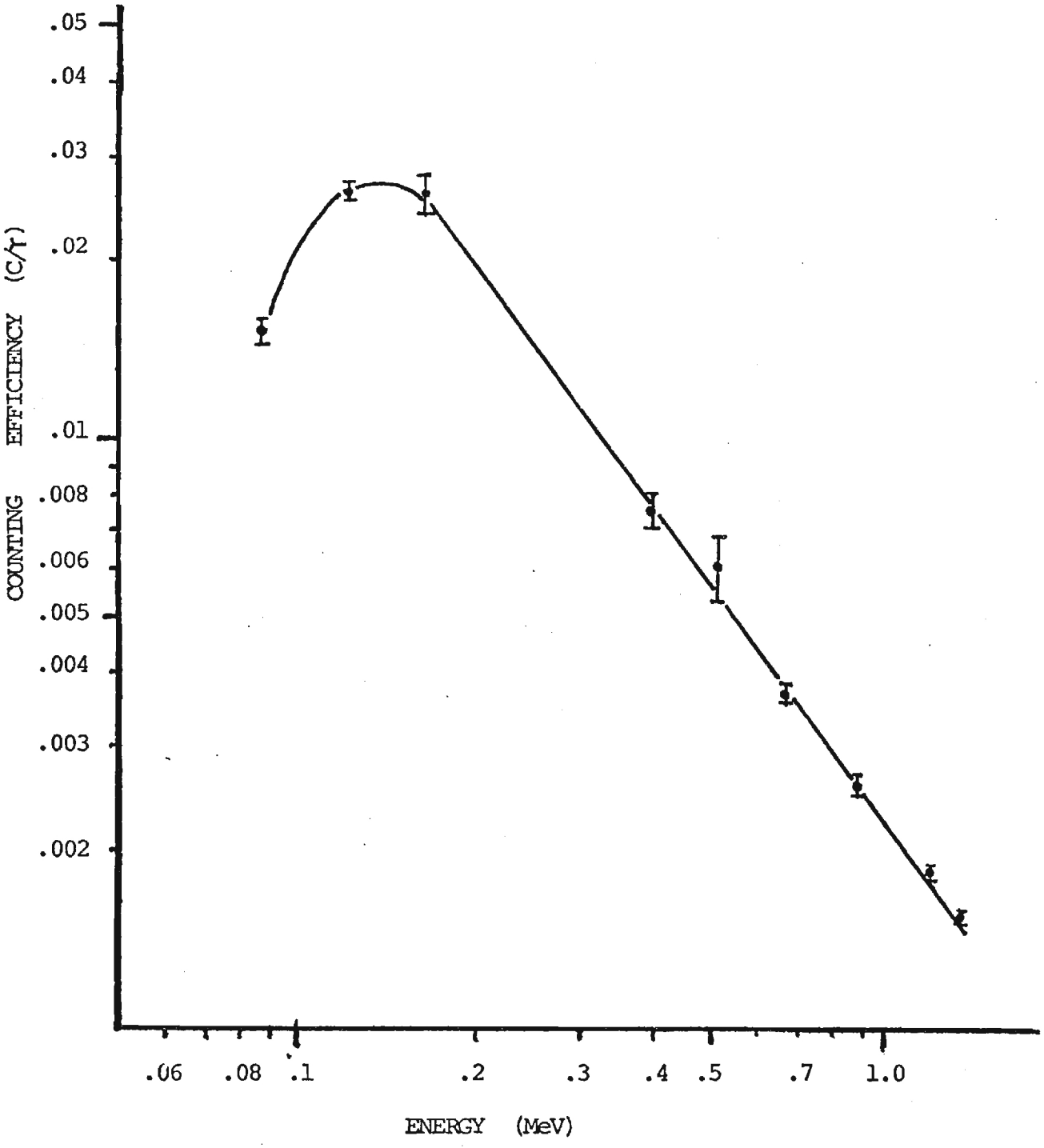


Figure 23. Counting Efficiencies

$$N = Ao + \sum_{i=1}^{n} (Ai + bi) - \frac{1}{2} (2n + 1) (A_n + b_n)$$

$$\sigma = \left\{ N + (n - \frac{1}{2}) (n + \frac{1}{2}) (A_n + b_n) \right\}^{1/2}$$

where Ao was defined as the response of the channel containing the greatest number of counts, and $A_1$, $A_2$, $\cdots$ $A_n$ were defined as the succeeding channel responses progressing down the low amplitude side of the peak. Similarly, channel responses on the high amplitude side of the peak were defined as $b_1$, $b_2$, $\cdots$ $b_n$.

An empirical equation was developed to relate the counting efficiency and the gamma-ray energy. The equation which fits with better than 9.1 percent accuracy in the range from 150 keV to 1332 keV was determined to be

$$\Sigma = 29.136\ E^{-1.374}$$

where

$\Sigma$ = Counting efficiency, C/$\gamma$

E = Gamma-ray energy, keV

Setting E equal to 412 keV for $^{198}$Au, the counting efficiency, including standard deviation, was determined to be $\Sigma = 0.00744 \pm 0.00083$ c/$\gamma$.

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E-26-632

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March 6, 1979

Research Contracts, Procedures
& Reports Branch
Contract Division
U. S. Department of Energy
P. O. Box E
Oak Ridge, Tennessee 37830

Reference: Contract No. EY-76-S-05-5814, A005

Gentlemen:

Enclosed in triplicate is the Statement of Costs and Final Voucher for the above referenced contract covering the period of December 1, 1977 through November 30, 1978.

If you have any questions or desire additional information, please let us know.

Sincerely,

David V. Welch, Manager
Grants & Contracts Acctg.

DVW/GS/bs
Enclosures
cc: Dr. K. Z. Morgan
Dr. L. E. Weaver
Mr. E. E. Renfro
Mr. A. H. Becker
File E-26-632

GEORGIA INSTITUTE OF TECHNOLOGY, ATLANTA, GEORGIA
U.S. Department of Energy
Statement of Costs

. Name and Address of Contractor: Georgia Institute of Technology
Atlanta, Georgia 30332

. Contract Number: EY-76-S-05-5814, A005

. Beginning and ending date of pertinent contract period: December 1, 1977 through November 30, 1978.

. Costs incurred during the pertinent contract period:

| | | |
|---|---|---|
| a. | Salaries and wages | $ 18,405.98 |
| b. | Equipment (see attached list) | -0- |
| c. | Travel (all domestic) | 1,502.25 |
| d. | Other direct costs | 1,181.02 |
| e. | Total direct expenditures | $ 21,089.25 |
| f. | Indirect charges | 12,516.07 |

. Total costs for items under Article A-II(a) for the pertinent contract period. $ 33,605.32

. Support cost - 100% $ 33,605.32

. Cumulative support cost $140,124.21

. Accumulated support ceiling 140,246.00

. The difference between lines 7 and 8 $ 121.79

I hereby certify that this report is true and correct to the best of my knowledge nd belief and that the costs listed herein were incurred in connection with the erformance of the research provided for under this contract and in accordance with he terms and conditions set forth therein.

K. Z. Morgan, Professor of Nuclear Engineering
Name and Title of Principal Investigator

Signature

3/6/79
Date

David V. Welch, Manager Grants & Contracts Accounting
Name and Title of Business Officer

Signature

3/6/79
Date

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GAO 5000
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TITLE David V. Welch, Manager
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